NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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LATERAL-CONTROL CHARACTERISTICS OF VARIOUS SPOILER ARRANGEMENTS AS MEASURED IN FLIGHT

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SUMMARY

The lateral-control characteristics of several spoiler arrangements located near the wing trailing edge were investigated in flight. It was found that, in all cases, the control response was satisfactory and that, except for a region of low spoiler effectiveness for small control deflections, the variation of rolling effectiveness with control deflection was smooth and nearly linear. The rolling effectiveness for a given spoiler deflection was found to increase with airspeed. The control forces varied smoothly but at an increasing rate with control deflection, leading to a low degree of control feel for small spoiler deflections. With a system which consisted of spoilers in combination with small wing-tip ailerons, the effectiveness and control-force characteristics were exceptionally good, especially at high speeds. The yawing characteristics of the various spoiler arrangements were more favorable than those usually associated with aileron control and the lateral control in inverted flight was adequate.

INTRODUCTION

With the current trend toward higher wing loadings and the desirability of lower landing speeds, increasing interest is being evinced in the characteristics of lateral-control systems permitting the use of large- or full-span flaps.

Results of previous wind-tunnel and flight investigations, reported in references 1 to 7, have indicated that one of the more promising lateral-control devices for use with full-span flaps is the circular-arc spoiler located near the wing trailing edge. Previous flight tests of this type of lateral-control surface (references 6 and 7) were limited to low speeds, and no control-force or hinge-moment measurements were obtained during those tests. Flight investigations, which included measurements of control-force, hinge-moment, and high-speed characteristics, were conducted at the Ames Aeronautical Laboratory for various spoiler-type lateral-control arrangements on three airplanes. The lateral-control characteristics from these investigations, determined chiefly in abrupt rudder-fixed rolls, of the following airplanes and systems are presented and discussed in this report:

1. A combination of circular-arc spoilers with wing-tip ailerons on a Northrop P-61A airplane, standard for this airplane. Tests were performed over a sizable speed range (maximum Mach number of 0.68), and individual spoiler and aileron hinge moments were measured.

2. Circular-arc spoilers alone on a Northrop P-61A airplane. Tests were conducted with the wing-tip ailerons locked in the neutral position.

3. Plug-type vented Zap spoilers on a Vought-Sikorsky OS2U-2 airplane modified to accommodate full-span Zap flaps.

4. Simple circular-arc spoilers on a Vought-Sikorsky OS2U-2 airplane modified to accommodate full-span Zap flaps.

5. Upper-surface flap-type spoilers on a normal OS2U-2 airplane, standard for this airplane. The tests were performed while the slotted wing flaps were fully deflected, under which condition the ailerons are dropped and inoperative, and the lateral control is supplied by the spoilers alone.

SYMBOLS

The symbols used in this report are defined as follows:

A_Z normal acceleration factor, the algebraic sum of the components, along the airplane Z-axis, of the airplane acceleration and the acceleration due to gravity, in terms of the standard gravitational unit (32.2 ft/sec^2)

b wing span, feet

c local wing chord, feet

$\bar{c}$ mean aerodynamic chord, feet

F lateral-control force, applied tangentially to the control wheel or normal to the control-stick grip, pounds

F_a lateral-control force due to aileron action, pounds

F_s lateral-control force due to spoiler action, pounds

H_a aileron hinge moment, positive when tending to move the aileron downward, inch-pounds

H_s spoiler hinge moment, positive when tending to move the spoiler downward, inch-pounds

h_p pressure altitude, feet

l control-stick length or wheel radius, inches

p rolling velocity, radians per second

$pb/2V$ tangent of the helix angle generated by the wing tips

r radius of spoiler, inches

V true airspeed, feet per second

V_i indicated airspeed, miles per hour

β sideslip angle, degrees

δ_a aileron angle, the algebraic difference between the angles of the two ailerons measured from the wing chord line (left when the left aileron is up), degrees

δ_c control-wheel or -stick deflection, degrees

δ_s spoiler angle, the angular deflection of the upward-deflected spoiler about the hinge line, as measured from the position for which the upper edge is coincident with the wing upper surface, degrees

DESCRIPTION OF LATERAL-CONTROL ARRANGEMENTS

The following is a description of the more important physical characteristics of the test lateral-control systems and airplanes. Detailed specifications and dimensions are given in the appendix.

Arrangement I - Circular-Arc Spoilers and Wing-Tip

Ailerons on a Northrop P-61A Airplane

This lateral-control system (standard on the Northrop P-61A airplane) consisted of a combination of upper-surface spoilers located forward of the flaps and small unsealed plain-flap-type ailerons at the wing tips. The spoilers were of a simple circular-arc type with the center of curvature coincident with the hinge line, and contained 3/4-inch-diameter holes which reduced the total spoiler area by approximately 20 percent. Details of the control surfaces are shown in figure 1 and 2. The wing slot through which the spoiler operated was provided with a faired seal on the lower wing surface, as shown in figures 1 and 3. The spoilers were partially mass-balanced and the ailerons were completely mass-balanced. The degree of mass unbalance and friction in the control system, as measured on the ground during slow movements of the control wheel, are indicated by the curves of figure 4. The kinematics of the control system, as measured under no-load conditions are shown in figure 5. The development of this lateral-control system is reported in reference 8.

The airplane was equipped with slotted flaps which extended approximately 82 percent of the wing semispan from the airplane center line. Details of the outboard flap panels, the slots of which were fabric-sealed, are shown in figure 3. A three-view drawing of the airplane is presented in figure 6; figure 7 shows the airplane with the flaps fully extended; and sketches of the flap and wing-section countours are presented in figure 8.

Arrangement II - Circular-Arc Spoilers Alone

on a Northrop P-61A Airplane

This arrangement was the same as Arrangement I except that both ailerons were fixed in the neutral position.

Arrangement III - Plug-Type Zap Spoilers on a Vought-

Sikorsky OS2U-2 Airplane with Full-Span Zap Flaps

This arrangement consisted of plug-type vented Zap spoilers installed on a Vought-Sikorsky OS2U-2 airplane modified to accomodate full-span circular-arc Zap flaps. Details of the spoilers and flap are presented in figure 9, and a view of the spoilers and flaps fully extended is shown in figure 10. The kinematics of the control system are presented in figure 11, and a three-view drawing of the airplane is shown in figure 12.

Arrangement IV - Circular-Arc Spoilers on a Vought-Sikorsky OS2U-2 (Zap) Airplane

The plug-type spoilers of Arrangement III were replaced with simple circular-arc-type spoilers having the center of curvature above the hinge line. Details of the surfaces are shown in figures 13 and 14, and the control-system kinematics are presented in figure 15.

Arrangement V - Flap-Type Spoilers on a Vought-Sikorsky OS2U-2 Airplane

This arrangement, standard on the Vought-Sikorsky OS2U-2 airplane, consisted of flap-type spoilers forward of the slotted flaps and wing-tip Frise-type ailerons. Details of the surfaces are shown in figures 16 and 17. As the flaps were lowered, a gradual transition from control by ailerons to control by spoilers occurred, and simultaneously the ailerons became drooped (both deflected downward). With the flaps fully deflected, lateral control was by spoilers alone, the ailerons remaining fixed in a drooped position (approx. 29° down). The tests reported herein were conducted for this condition, the kinematics for which are shown in figure 18. A three-view drawing of the airplane is presented in figure 19.

INSTRUMENTATION

The test airplanes were equipped with standard NACA photographically recording instruments by means of which the following quantities were measured: indicated airspeed, lateral-control-surface or control-stick positions, angular velocities, lateral-control force, normal acceleration, and angle of sideslip.

A yaw vane and a free-swiveling airspeed head were mounted on booms extending approximately one chord length ahead of the wing tips.

For the tests with Arrangements I and II, individual spoiler and aileron hinge moments were measured by means of resistance-type strain-gage units mounted on the push-pull rods of the surfaces and connected to a recording oscillograph.

TESTS

The flight tests reported herein consisted primarily of abrupt left and right rudder-fixed rolls at various airspeeds for the following combinations of flap and power settings:

Condition	Power setting[1]	Flap and gear setting	Cowl-flap position
Power-on clean	Normal rated	Up[2]	Open
Wave-off	Normal rated	Down	Open
Glide	Off	Up[2]	Closed
Landing	Off	Down	Closed

[1]See appendix for engine-power ratings.
[2]Gear retractable for Arrangements I and II only.

The airplane gross weights and center-of gravity locations at take-off for all the tests corresponded approximately to the normal values given in the appendix. Except as otherwise specified, the tests were performed at pressure altitudes of from 6000 to 10,000 feet.

RESULTS AND DISCUSSION

Response Characteristics

The rolling response of an airplane to lateral-control deflections may be measured by the time required for the establishment of the maximum rolling acceleration following the abrupt deflection of the controls to a predetermined position. Criterions based on previous test results and pilots' opinions have been promulgated in references 9, 10, and 11 in the form of maximum satisfactory time-lag values of 0.2 second (reference 9) and 3.75 c/V seconds (references 10 and 11).

Time histories of typical abrupt rudder-fixed rolls are presented in figure 20 for the various lateral-control arrangements. These records show that in the critical low-speed conditions the lag was equal to or less than the values mentioned in the preceding paragraph. Although in a few cases the pilots noticed lag with spoiler control which they believed slightly greater than that with normal aileron control, the response characteristics of the various test control systems were considered satisfactory.

These response characteristics are in agreement with the results of the investigations, reported in references 3, 12, and 13, which have shown that the lag with spoiler-type surfaces is a function of the chordwise location on the wing and that, for the spoiler locations for the tests reported herein (70 or 80 percent of the local wing chord from the leading edge), the lag should be satisfactorily small.

At high airspeeds, abrupt lateral-control deflections caused a sharp momentary decrease in normal acceleration (fig. 20(a)), an effect associated with the sudden decrease in lift due to spoiler action. This characteristic was not noticeable at low speeds and was not considered seriously objectionable by the pilots.

The effect on the response characteristics of changes in flap and power settings appeared to be negligible.

Rolling Effectiveness

Values of $pb/2V$ corresponding to the peak rolling velocities were determined from records similar to those shown in figure 20, and are presented in figure 21 as a function of change of spoiler angle from that for balance. These curves show that for all test arrangements and conditions the rolling effectiveness varied smoothly with spoiler angle but that a region of low effectiveness was present for small spoiler angles. The latter effect may be attributed to the low effectiveness of the spoiler when operating in the wing boundary layer. As would be expected, this effect was less pronounced with spoiler-aileron control (Arrangement I) than with pure spoiler control (Arrangement II). Although not considered seriously objectionable from a piloting standpoint, the low effectiveness near neutral led toward a tendency to overcontrol somewhat at low speeds, such as in approaches and landings.

The decrease in the slope $d(pb/2V)/d\delta_s$ with increasing spoiler angle for sizable control deflections resulted from the fact that, as shown in previous investigations, $pb/2V$ is more nearly proportional to the spoiler height above the wing than to the spoiler angle. The variation of $pb/2V$ with spoiler height was found to be nearly linear. The results for Arrangements III and IV (fig. 21) and for a modified version of Arrangement IV indicate that for a given spoiler height, the effectiveness of these radically different surfaces was of the same order.

From a pilot's standpoint, it is desirable to have a linear variation between $pb/2V$ and control-wheel or -stick deflection. Owing to the relatively large amount of differential associated with spoiler systems (see figs. 5, 11, 15, and 18), conversion of spoiler angle to wheel or stick deflection results in very nearly linear variations of $pb/2V$ with cockpit control deflection.

The usual criterion for the rolling power of a lateral-control surface is the maximum value of the rolling effectiveness pb/2V attainable with full control deflection. Values of 0.07 or greater have been found adequate for satisfactory handling qualities of most airplanes (references 9, 10, and 11) but for fighter-type airplanes, values of 0.09 or greater are considered desirable. (See reference 10.) Maximum values of pb/2V corresponding to full control deflection, as obtained from figure 21, are given in the following table:

Condition	Arrangement				
	I	II	III	IV	V
Power-on, clean					
110 mph	0.070	0.038	0.073	0.070	-----
265 mph	.072	.049	-----	-----	-----
Wave-off					
100 mph	.096	.053	.070	.070	0.060

It is estimated that, should the spoilers for Arrangement II be extended to the wing tips, the maximum values of pb/2V probably would be increased about 40 percent. It should be pointed out that the lateral-control surfaces of Arrangement I were designed to give a maximum pb/2V of 0.07, and a method by which a spoiler system can be designed to give a specified value of maximum pb/2V is indicated in reference 8.

Effect of airspeed.- The curves of figure 21 show that, for the spoilers tested, pb/2V for a given spoiler deflection increased with airspeed. It is noted that this effect, which is not characteristic of aileron control, is less for the spoiler-aileron system of Arrangement I than for the corresponding pure spoiler system (Arrangement II). The superiority of spoilers over ailerons in this respect is due in part to the smaller torsional loads associated with spoilers and hence the smaller reduction in rolling effectiveness due to wing twist, especially at high speeds. Additional factors which contribute to this increase in pb/2V with airspeed are increases in spoiler effectiveness with decreases in wing angle of attack, the more favorable yawing tendencies of spoilers especially at high speeds, and increases in Mach number. High-speed wind-tunnel data of references 14 and 15 and recent data on file at Ames laboratory obtained in the Ames 1- by $3\frac{1}{2}$-foot high-speed wind tunnel have shown that the spoiler effectiveness increased with Mach number up to values slightly above the critical, beyond which a sharp decrease occurred.

Effect of flap deflection.- Comparison of the curves of figure 21 for the various conditions shows that, with power either on or off, deflection of the flaps appreciably increased the $pb/2V$ obtained with a given spoiler deflection at the same airspeed.

Results of flight tests with Arrangement I and of wind-tunnel tests[1] obtained with a two-dimensional model wing showed that with a deflected slotted flap the spoiler effectiveness was zero or of the wrong sign at small spoiler angles. It was found that with the flap slot sealed, as was the outer panel slot for Arrangements I and II, this effect was eliminated, but the flap effectiveness was reduced. A possible explanation of this characteristic is that the spoiler, when deflected a small amount, causes an increase in the air flow through the flap slot, and the resulting increased lift of the flap opposes the wing-lift reduction due to spoiler action.

Effect of power.- Comparison of the curves for the power-on clean conditions (fig. 21(a)) with those for the glide condition (fig. 21(c)) shows that, especially at low airspeeds, $pb/2V$ for Arrangement I was markedly increased with application of power, due chiefly to the increase in slipstream velocity over the spoilers which were located sufficiently inboard to be affected. This effect, to a slightly larger degree, would also be characteristic of Arrangement II, and, as would be expected, a similar effect of power was noted for Arrangements III and IV but not for Arrangement V.

Control-Force and Hinge-Moment Characteristics

Changes in lateral-control force from the values for balance were determined from time histories similar to figure 20 and are presented in figure 22 as a function of change in spoiler angle. These data represent the maximum values neglecting the initial peak values and oscillations of control force attributed to the relatively large inertia of the control systems. The corresponding values of individual spoiler and aileron hinge moments for Arrangements I and II are presented in figures 23 to 26. The measured spoiler hinge moments include the effects of spoiler mass unbalance, and these values have been designated as total hinge moments. The total hinge moments corrected for the effects of static mass unbalance from figure 4 are denoted aerodynamic hinge moments. These hinge moments were measured at the initial maximum values (neglecting inertia effects).

Spoiler-aileron control.- The curves of figure 22 for Arrangement I show smooth and nearly linear variations of control force with spoiler

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[1]From data on file at Ames laboratory.

angle for all conditions. The pilots considered the magnitude of these forces exceptionally good (not excessive at high speeds and sufficient for feel at low speeds) in relation to the corresponding values of $pb/2V$.

The curves of figure 23 show an increasing rate of change of hinge moment with respect to spoiler angle $dH_s/d\delta_s$ as the spoiler was deflected from neutral. Small negative aerodynamic hinge moments were present over a sizable spoiler-angle range near zero, both up and down, especially at low airspeeds. As shown in previous investigations, these effects are characteristic of this type of spoiler. It is noted that the mass unbalance in the system was sufficient to counteract the negative hinge moments in most cases. The variations of aileron hinge moment with aileron angle (fig. 24) were essentially linear in all cases, as is characteristic of a plain control surface without aerodynamic balance.

The contribution of both spoiler and aileron action to the total lateral-control forces of Arrangement I has been computed from the hinge moments (figs. 23 and 24) and the kinematics of the system (fig. 5) by means of the following equations:

$$F_s = \frac{H_s}{l} \frac{d\delta_s}{d\delta_c} \tag{1}$$

$$F_a = \frac{H_a}{l} \frac{d\delta_a}{d\delta_c} \tag{2}$$

These values, along with the total control forces measured directly, are presented in figure 25 as functions of spoiler angle. The reliability of the hinge-moment data presented herein is indicated by the close agreement between the computed total force curves and the test points. The curves of figure 25 show that the contribution of the ailerons to the total control force is paramount and that the spoiler contribution is small except for large spoiler angles. This predominance of aileron influence is largely responsible for the desirable total control-force variation with spoiler angle.

<u>Circular-arc-spoiler control.</u>- The curves of figure 22 for the circular-arc-spoiler systems (Arrangements II, III, IV) show a region of low forces for small spoiler angles and an increase in the rate of change of control force with spoiler angle $dF/d\delta_s$ as the spoiler angle is increased. The hinge-moment data of Arrangement II (fig. 26) show similar characteristics. The low forces for small spoiler angles result partially from spoiler operation in the low-velocity region of the wing boundary layer.

The control forces for Arrangement II (fig. 22) were considered too light for desirable control feel and for proper self-centering tendencies of the control. Larger control forces could be provided by the action of a suitable plate installed normal to the spoiler upper edge, and the control feel could be further improved by some mechanical means, such as the use of springs in the system or a spoiler upper-edge plate which has a differential motion.

For spoilers such as those used in Arrangement III, additional effects on the hinge-moment characteristics are encountered, such as circulation around the upper plate, around the vane, and through the various vent holes. Results of supplementary flight tests of Arrangement III with minor modifications showed that a reduction in the upper-plate area resulted in an approximately proportional reduction in the control forces and a rotation of the vane nose upward resulted in very slight decreases in control force. It appeared that nearly all the control force originated from the upper plate.

An additional means of providing large enough control forces for control feel is to have the spoiler center of curvature at a small distance above the hinge line, as in Arrangement IV. The curves of figure 22 show the large forces resulting from the small offset used. It is noted that the general nature of the curves for Arrangement IV is similar to that for the other circular-arc spoilers. Supplementary tests conducted with these spoilers modified so that the center of curvature was even farther above the hinge line resulted in proportionately higher control forces.

It appears that some improvement in the variation of control force with spoiler angle could be effected through a spoiler design in which the center of curvature varied along the height so as to give a larger rate of hinge-moment increase at low spoiler angles and a reduced rate at larger angles. However, the use of offset-type circular-arc spoilers necessitates an increase in the gap in the upper wing surface, resulting in a consequent adverse effect on the aerodynamic characteristics of the wing.

Flap-type spoiler.- As would be expected, the curves of figure 22 for the flap-type spoilers (Arrangement V) show nearly linear variations of control force with spoiler angle. The pilots considered the control forces too large in view of the relatively low rates of roll obtainable with this arrangement.

Yawing Characteristics

The yawing and sideslip characteristics of the various spoiler arrangements are shown by the time histories of figure 20 and by the variation of sideslip angle with spoiler angle presented in figure 27.

The values of side-slip angle shown in figure 27 represent the change in side-slip angle from the values for balance to those corresponding to maximum rolling velocity.

The data of figure 27 indicate relatively small adverse yawing moments at low airspeeds and a tendency toward favorable yawing moments at high speeds. These yawing characteristics are more desirable than those usually associated with a conventional aileron-control system. The lower adverse yawing effects of spoilers provide a decided advantage for this type of control over aileron control in that the rudder control required in properly coordinated turn entries and exits is less. The advantages of spoilers for use with two-control systems is apparent from these characteristics. The more desirable yawing characteristics of spoilers are due to the predominance of the favorable profile-drag effects over the adverse induced-drag effects.

Effects of Altitude

Results of abrupt rudder-fixed rolls with Arrangement I at a pressure altitude of approximately 27,000 feet are presented in figure 28. The curves are similar in character to the corresponding curves at normal altitude (figs. 21, 22 and 27), although there are slight differences in effectiveness and some increase in control force. No sizable effect of altitude on the sideslip characteristics is apparent.

Characteristics near the Stall

In order to obtain an indication of the lateral-control effectiveness near the stall, abrupt rudder-fixed rolls with Arrangement I were made during the early stages of the stall. Typical time histories are presented in figure 29, in which oscillations of the pitching velocity indicate that the airplane was in an incipient stall during these tests. The roll following abrupt deflection of the control was in the correct direction and the lag was desirably low. The pilots considered the lateral control in the stall region to be excellent, but these characteristics are probably due in part to the unusually good stalling pattern of the wing itself (characterized by an early wing-center-section breakdown).

Stalls conducted with Arrangement III, for which typical time histories are presented in figure 30, showed that the spoilers were not very effective in controlling the rolling motions in the stall, particularly with flaps up. With flaps down, the control was fairly good. The pilots considered that the lateral-control effectiveness of this arrangement in the stall was about the same as that which would be expected from ailerons.

Characteristics in Inverted Flight

In order to determine the effectiveness of spoilers in inverted flight, a maneuver was made with Arrangement II in which the airplane was rolled left to approximately inverted flight. While in this attitude, the airplane was then rolled abruptly to the right, an attempt being made to maintain a constant rudder angle. A time history of this maneuver is presented in figure 31, which shows that the spoilers produced a rolling motion in the correct direction while in inverted flight and that the lag was not excessive. Favorable yawing motions are also indicated. The pilots considered the spoiler effectiveness in inverted flight entirely adequate.

CONCLUDING REMARKS

The flight tests reported herein indicated that spoilers located near the wing trailing edge may supply satisfactory lateral-control characteristics which are in some respects superior to those of ailerons.

It was found that the spoiler effectiveness, as measured by maximum $pb/2V$ in abrupt rudder-fixed rolls, was approximately proportional to the cockpit control deflection except for a region of low effectiveness for small spoiler deflections and that the spoiler effectiveness increased appreciably with airspeed, a characteristic not normally associated with ailerons. The corresponding control forces varied smoothly and in the proper direction but at an increasing rate with spoiler deflection, and the control forces near neutral spoiler position were very low.

The response characteristics and the control in inverted flight and near the stall were found to be entirely satisfactory for the spoiler arrangements for which these characteristics were investigated. All the spoiler arrangements exhibited satisfactory yawing characteristics which were more favorable than those associated with ailerons. Changes in normal acceleration following abrupt deflections of the spoilers were not noticeable at low speeds and were not seriously objectionable at high speeds.

The results of these flight tests indicate that the optimum lateral-control arrangement tested was the combination of circular-arc spoilers with the center of curvature coincident with the hinge line and small plain ailerons at the wing tip. In addition to permitting the use of large-span flaps, such an arrangement realizes the combined advantages of spoiler yawing characteristics, spoiler effectiveness (particularly at high speeds), and aileron hinge-moment characteristics, and hence possesses lateral-control characteristics superior to those of a conventional aileron system.

The present test results also indicate that, should a full-span flap be desired, a circular-arc spoiler with a suitable plate normal to the upper edge of the spoiler would provide satisfactory lateral-control characteristics if a low degree of control feel near neutral would be acceptable. The control feel with this arrangement, however, could possibly be improved by mechanical means such as the use of springs in the control system or a spoiler upper-edge plate which has a differential motion.

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REFERENCES

1. Wenzinger, Carl J., and Bamber, Millard J.: Wind-Tunnel Tests of Three Lateral-Control Devices in Combination with a Full-Span Slotted Flap on an NACA 23012 Airfoil. NACA TN No. 659, 1938.

2. Wenzinger, Carl J., and Rogallo, Francis M.: Wind-Tunnel Investigation of Spoiler, Deflector and Slot Lateral-Control Devices on Wings with Full-Span Split and Slotted Flaps. NACA Rep. No. 706, 1941.

3. Shortal, J. A.: Effect of Retractable-Spoiler Location on Rolling- and Yawing-Moment Coefficients. NACA TN No. 499, 1934.

4. Rogallo, Francis Melvin, and Swanson, Robert St. Clair: Wind-Tunnel Development of a Plug-Type Spoiler-Slot Aileron for a Wing with a Full-Span Slotted Flap and a Discussion of its Application. NACA ARR, Nov. 1941.

5. Rogallo, Francis Melvin, and Spano, Bartholomew S.: Wind-Tunnel Investigation of a Spoiler-Slot Aileron on an NACA 23012 Airfoil with a Full-Span Fowler Flap. NACA ARR, Dec. 1941.

6. Soulé, H. A., and McAvoy, W. H.: Flight Investigation of Lateral-Control Devices for Use with Full-Span Flaps. NACA Rep. No. 517, 1935.

7. Wetmore, J. W.: Flight Tests of Retractable Ailerons on a Highly Tapered Wing. NACA TN No. 714, 1939.

8. Ashkenas, I. L.: The Development of a Lateral-Control System for Use with Large-Span Flaps. NACA TN No. 1015, 1946.

9. Gilruth, Robert Rowe: Requirements for Satisfactory Flying Qualities of Airplanes. NACA ACR, April 1941. (Classification changed to Restricted Oct. 1943.)

10. Anon.: Stability and Control Characteristics of Airplanes. Spec. No. R-1815A, U. S. Army Air Forces, Apr. 7, 1945.

11. Anon.: Specification for Stability and Control Characteristics of Airplanes. Spec. No. SR-119A, Bur. Aero., Navy Dept., Apr. 7, 1945.

12. Weick, Fred E., and Shortal, Joseph A.: Development of the NACA Slot-Lip Aileron. NACA TN No. 547, 1935.

13. Shortal, Joseph A.: Wind-Tunnel and Flight Tests of Slot-Lip Ailerons. NACA Rep. No. 602, 1937.

14. Laitone, Edmund V.: An Investigation of the High-Speed Lateral-Control Characteristics of a Spoiler. NACA ACR No. 4C23, 1944.

15. Laitone, Edmund V., and Summers, James L.: An Additional Investigation of the High-Speed Lateral-Control Characteristics of Spoilers. NACA ACR No. 5D28, 1945.

APPENDIX

DETAILS OF TEST AIRPLANES AND LATERAL-CONTROL SYSTEMS

Arrangements I and II

Airplane

Type	Northrop P-61A-5
Length (over-all)	48 ft 9 in.
Height (thrust-line level)	14 ft 8 in.
Test gross weight	26,800 lb
Test center-of-gravity position	0.276 M.A.C. (gear up)

Wing

Span	66.0 ft
Area	662.4 sq ft
Mean aerodynamic chord	126.7 in.
Aspect ratio	6.7
Dihedral of chord plane	
Inner panel	4°
Outer panel	2°
Sweepback of leading edge	0°
Incidence of chord line with thrust line	1.5°
Airfoil section	
Root	Zap 15 percent thick
Tip	Zap 13 percent thick

Flaps

Type	Slotted (outboard panels sealed)
Deflection	60°
Span (over-all)	55 ft
Chord	20 percent of wing chord
Area	124.6 sq ft

Spoilers (each)

Type	Circular-arc, perforated
Deflection	65° up, 27.5° down
Span	11.16 ft
Radius of forward face	9 percent of local wing chord
Area	9.5 sq ft
Location of forward face	72 percent of local wing chord

Ailerons (each)

Type	Plain flap (unbalanced, radius-nose)
Deflection	
Left	22.7° up, 21.5° down
Right	21.5° up, 21.3° down

Span	57 in.
Chord aft of hinge line	17 percent of local wing chord
Area	5.5 sq ft

Lateral control

Type	Wheel
Wheel diameter	13.9 in.

Engines

Type	Radial, air-cooled, 18-cylinder, double row
Manufacturer	Pratt and Whitney
Number	R-2800-65
Reduction gear ratio	0.5:1
Rating (each)	
Take-off	2000 bhp at 2700 rpm and 54.0 in. Hg at sea level
Normal	1675 bhp at 2550 rpm and 44.5 in. Hg at 8400 ft

Propellers (each)

Type	Constant-speed full-feathering
Manufacturer	Curtiss-Wright Corp.
Diameter	12 ft 2 in.
Number of blades	Four

Arrangement III

Airplane

Type	Vought-Sikorsky OS2U-2 modified to accommodate full-span Zap flaps
Length (over-all)	31.0 ft
Height (thrust-line level)	12 ft $11\frac{1}{8}$ in.
Test gross weight	4960 lb
Test center-of-gravity position	0.284 M.A.C.

Wing

Span	36.0 ft
Area	205.8 sq ft
Mean aerodynamic chord	72.5 in.
Aspect ratio	6.3
Dihedral of chord plane	7°
Sweepback of leading edge	$2^{\circ}51'$
Incidence of chord line with thrust line	3°
Airfoil section	
Root	Zap 17.25 percent thick
Tip	Zap 12 percent thick

Flaps (each)

Type	Zap circular-arc

Deflection. . . . . $41^{\circ}55'$
Span. . . . . 15 ft 7 in.
Area. . . . . 19.16 sq ft

Spoilers (each)
Type. . . . . Zap plug-type vented
Deflection
Left . . . . 37.8° up, 0.75° down
Right. . . . . 42.0° up, 2.2° down
Span. . . . . 10 ft 4.8 in.
Area (upper plate). . . . . 13.46 sq ft

Lateral control
Type. . . . . Stick
Stick length. . . . . 35 in.

Engine
Type. . . . . Radial, air-cooled, nine-cylinder, single-row
Manufacturer. . . . . .Pratt and Whitney
Number. R-985-48
Reduction gear ratio. . . . . Direct drive
Rating
Take-off . . . . . . 450 bhp at 2300 rpm and 35.5 in. Hg at sea level
Normal . . . . . . 400 bhp at 2200 rpm at sea level and 5500 ft

Propellers
Type. . . . . Constant-speed
Manufacturer. . . . . Hamilton Standard
Diameter. . . . . 8.50 ft
Number of blades. . . . . Two

Arrangement IV

The details are the same as those for Arrangement III, except as follows:

Spoilers (each)
Type. . . . . Simple circular-arc
Deflection
Left . . . . 47° up, 5.5° down
Right. . . . . 52° up, 8.5° down

Arrangement V

Airplane
Type. . . . . Vought-Sikorsky OS2U-2

Length (over-all)	30 ft 1 in.
Height (thrust-line level)	12 ft $6\frac{5}{8}$ in.
Test gross weight	4717 lb

Wing

Span	35 ft $10\frac{11}{16}$ in.
Area	261.9 sq ft
Mean aerodynamic chord	89.5 in.
Aspect ratio	4.92
Dihedral of chord plane	7°
Sweepback of leading edge	0°
Incidence of chord line with thrust line	3°

Flaps (each)

Type	Slotted-deflector-plate, spring-loaded to decrease deflection with increasing loads
Span	51 percent of wing semispan
Chord aft of hinge line	23 percent of local wing chord
Area aft of hinge line	17.5 sq ft

Spoilers (each)

Type	Flap-type, ventilated and paddle-balanced
Deflection	
Left	49.0° up, 3.5° down
Right	53.0° up, 3.5° down
Span	41 percent of wing semispan
Chord, average	10 percent of local wing chord
Area	4.98 sq ft

Ailerons (each)

Type	Frise
Span	31 percent of wing semispan
Chord, average aft of hinge line	17.2 percent of local wing chord
Area aft of hinge line	6.7 sq ft
Droop	29° at full flap deflection

Lateral control

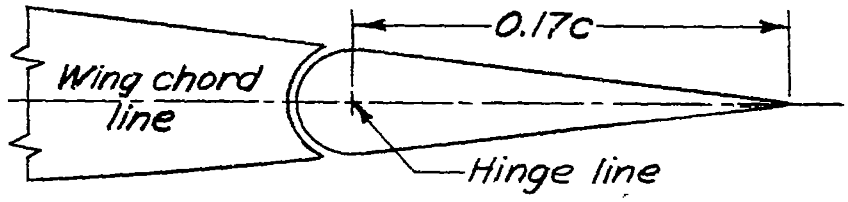
Type	Stick
Stick length	35 in.

Engine

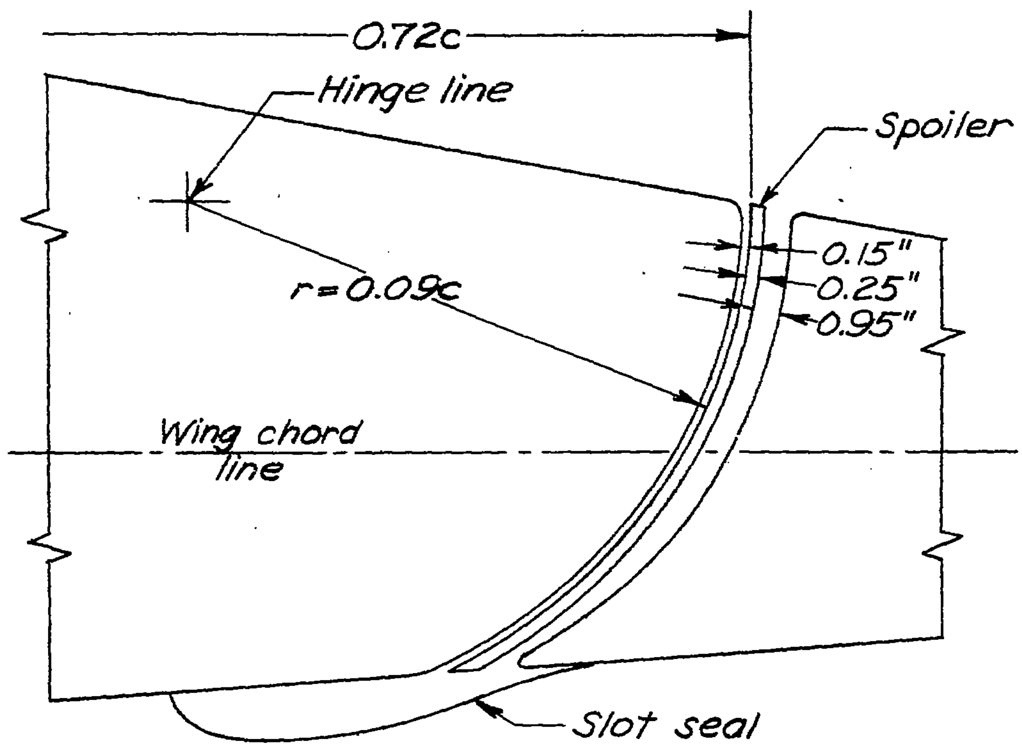
Type	Radial, air-cooled
Manufacturer	Pratt and Whitney
Number	R-985-50
Reduction gear ratio	Direct drive
Rating	
Take-off	450 bhp at 2300 rpm and 35.5 in. Hg at sea level
Normal	400 bhp at 2200 rpm at sea level and 5500 ft

Propeller

Type	Constant-speed
Manufacturer	Hamilton Standard
Diameter	8.50 ft
Number of blades	Two



Aileron (fixed in neutral position for Arrangement II) - Extends from 0.835 semispan to wing tip



Spoiler - Extends from 0.49 to 0.83 semispan

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Figure 1.- Lateral control surfaces. Arrangements I and II.

Figure 2.- Spoiler and aileron fully deflected, inboard cover plate open. Arrangement I.

Figure 3.- Outer wing panel showing seals over flap and spoiler slots. Arrangements I and II.

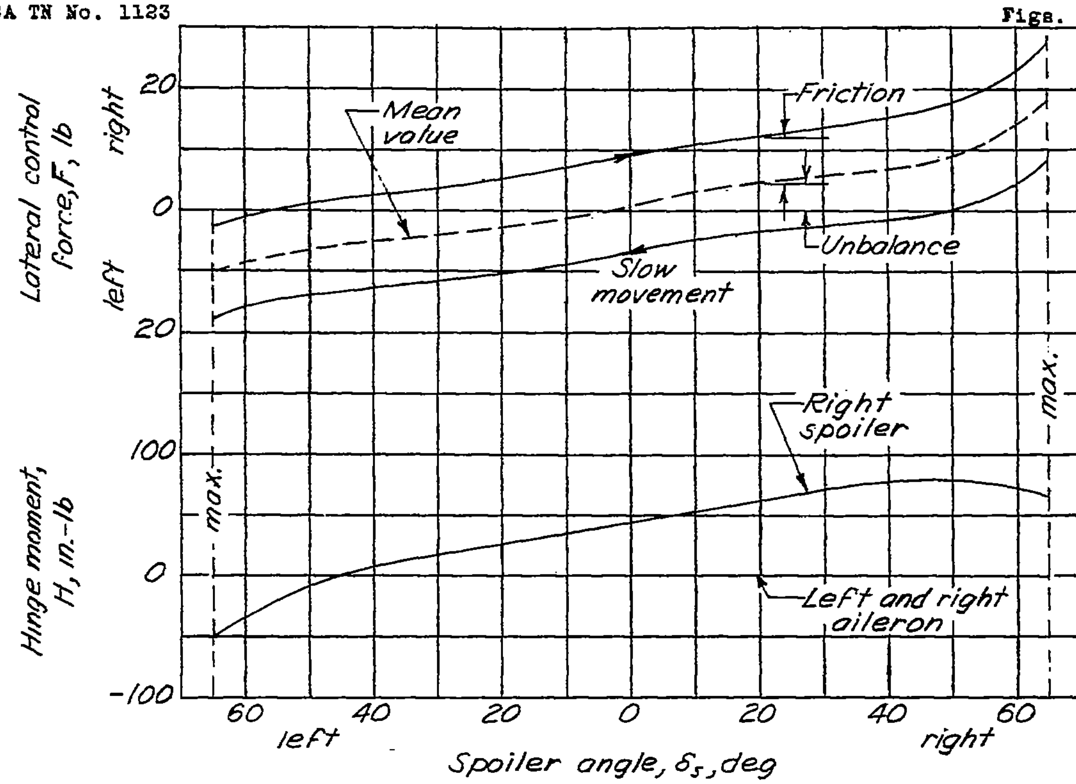


Figure 4.- Variation of lateral control force and hinge moment with spoiler angle under no-load condition. Arrangement I.

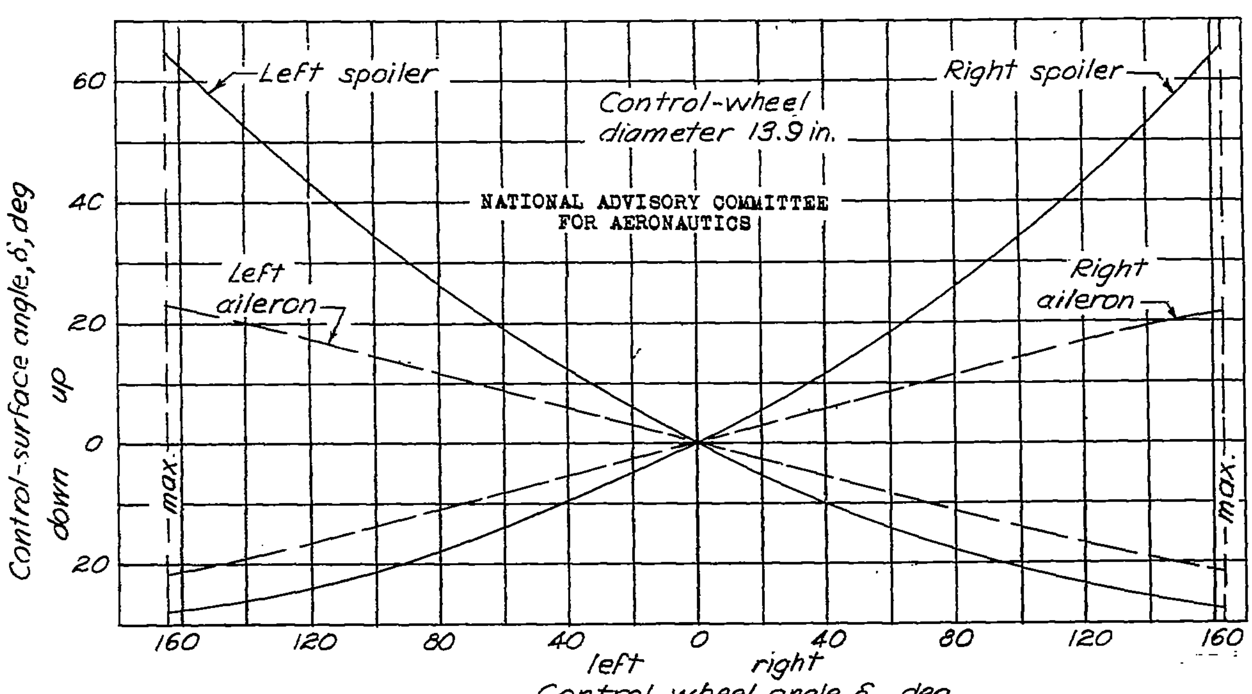


Figure 5.- Variation of lateral control-surface angles with control-wheel angle under no-load condition. Arrangement I.

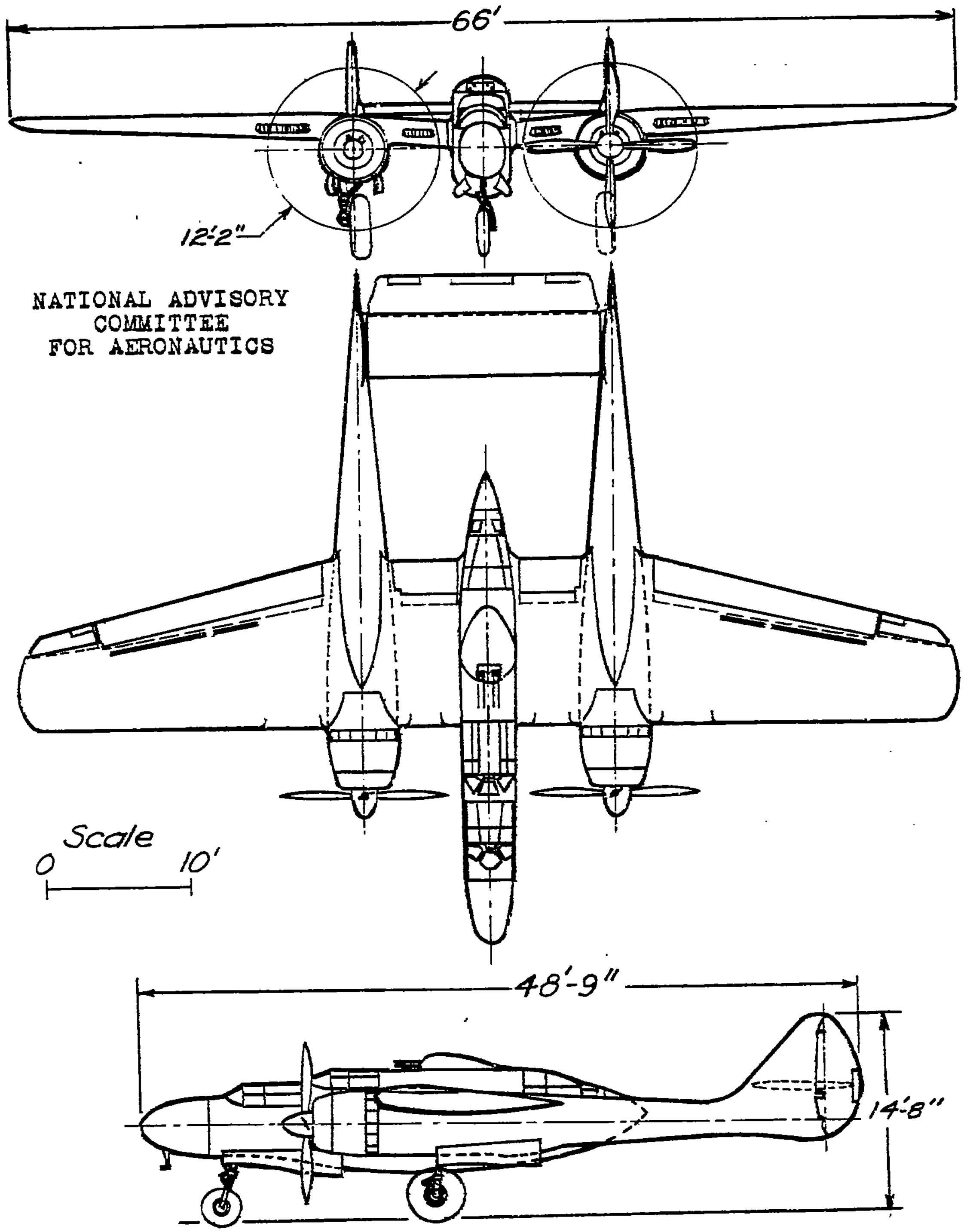


Figure 6.-Three-view drawing of the Northrop P-61A-5 airplane. Arrangements I and II.

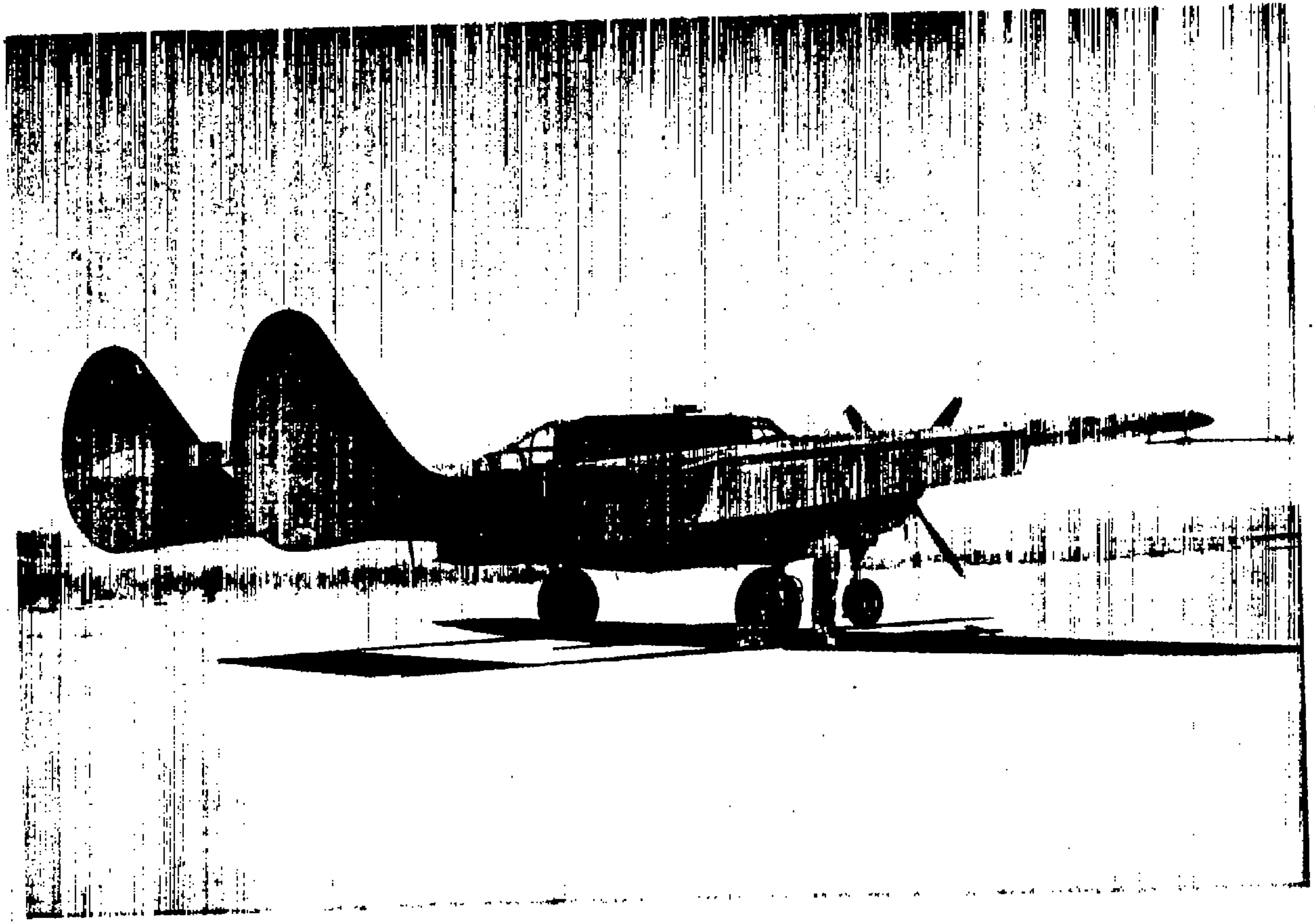
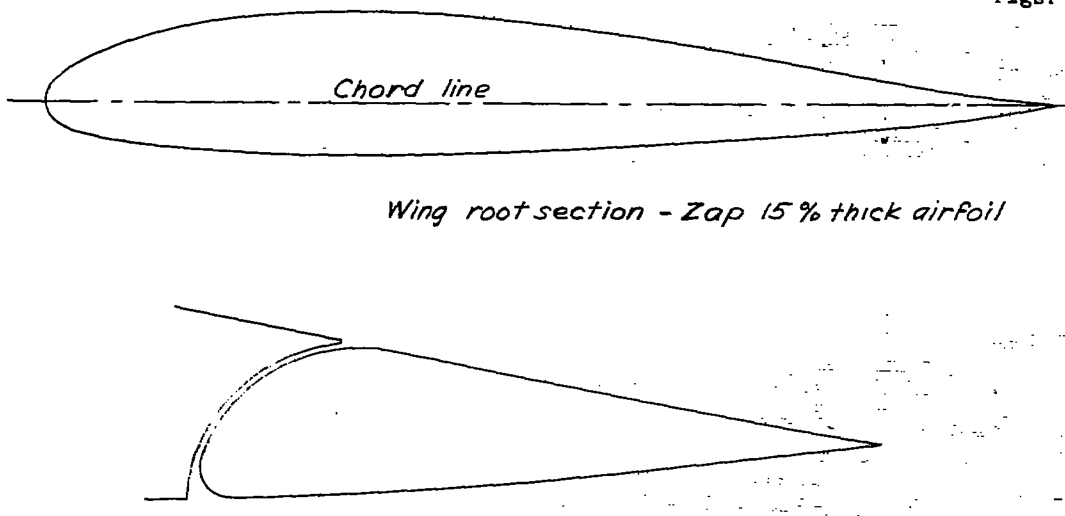


Figure 7.- Northrop P-61A-5 airplane with flaps fully extended.



Wing root section - Zap 15% thick airfoil

Flap section

Figure 8.- Wing and flap section contours. Arrangements I and II.

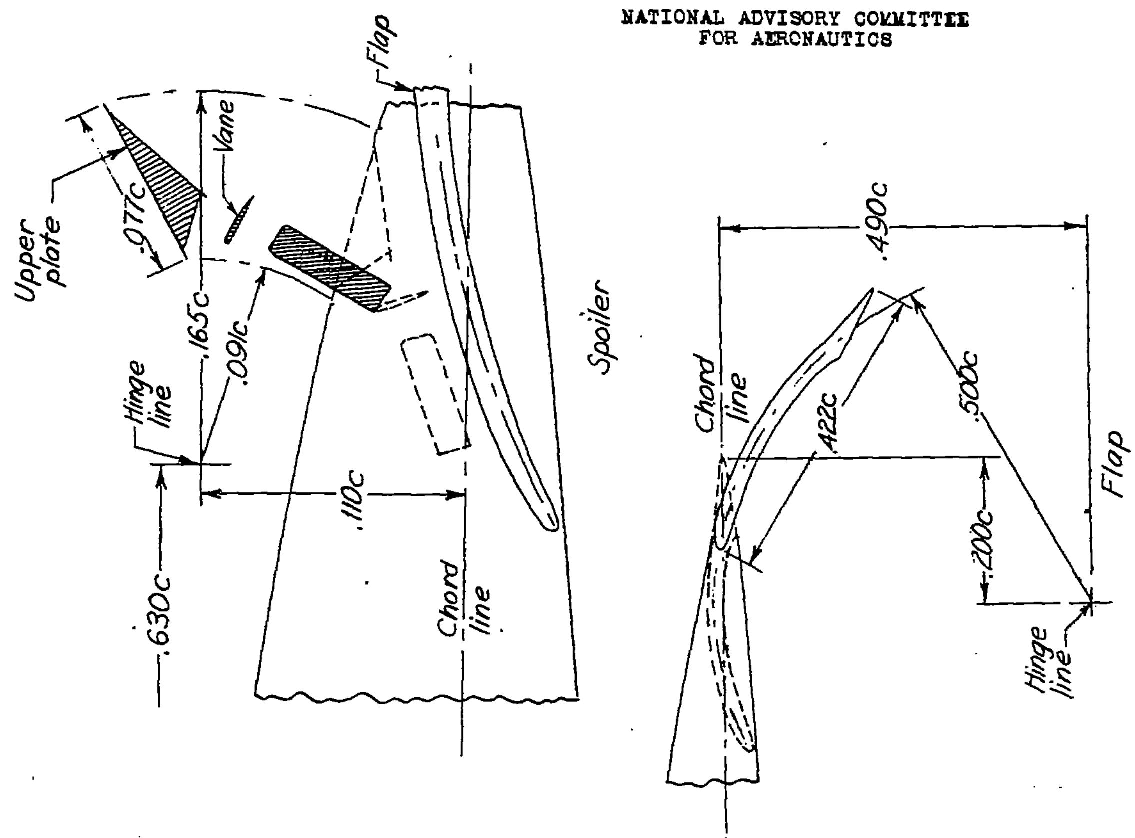


Figure 9.- Spoiler and flap. Arrangement III.

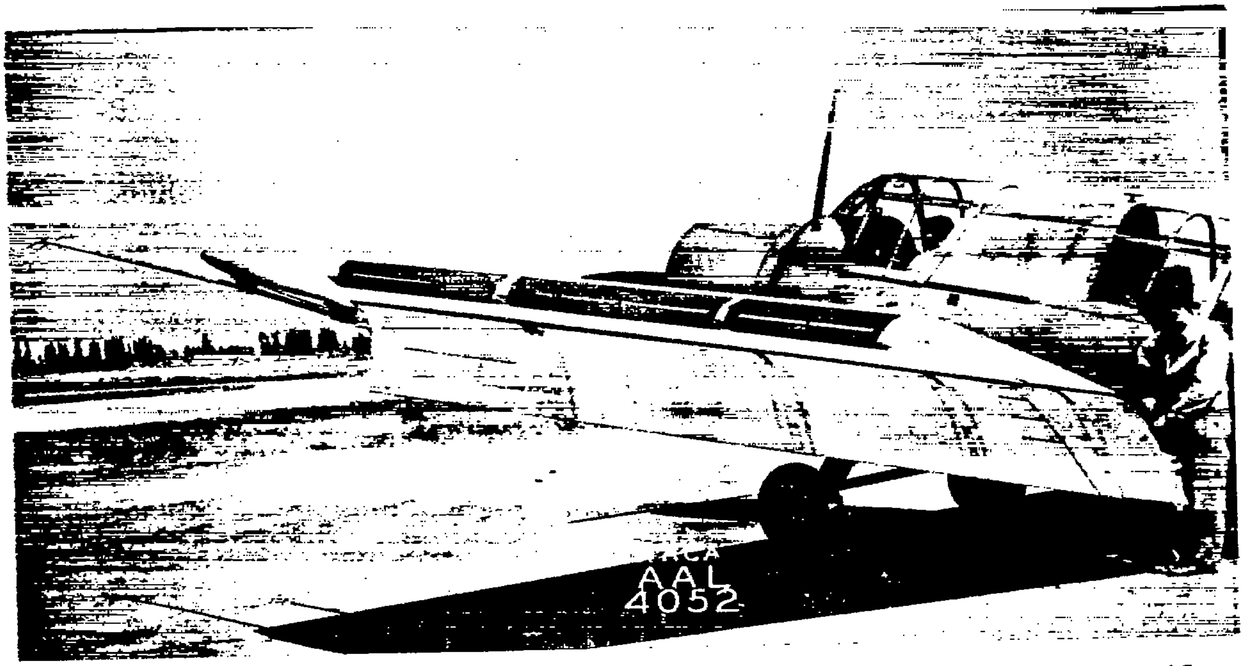


Figure 10.- Vought-Sikorsky OS2U-2 (Zap) airplane with spoilers and flaps fully deflected. Arrangement III.

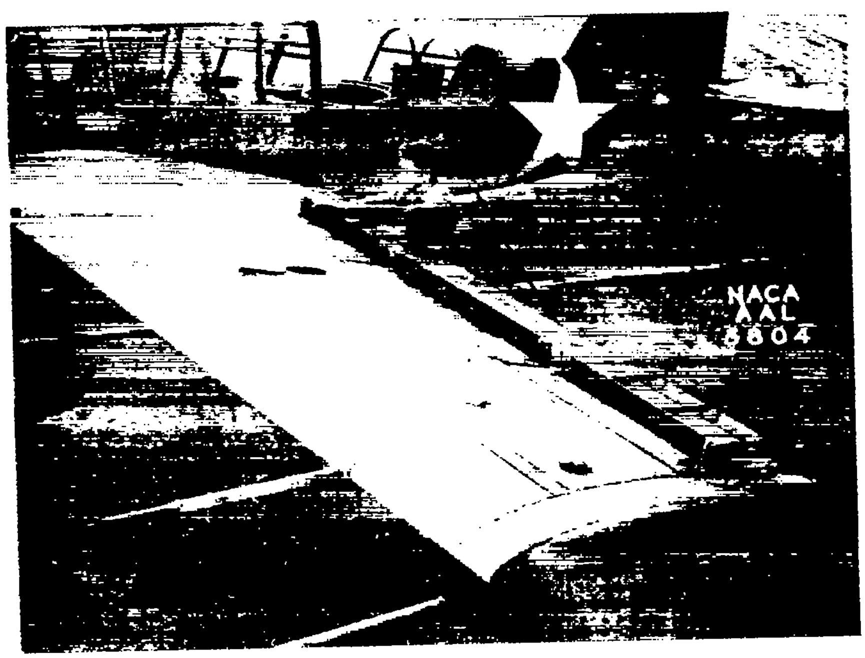


Figure 14.- Vought-Sikorsky OS2U-2 (Zap) airplane with spoilers fully deflected. Arrangement IV.

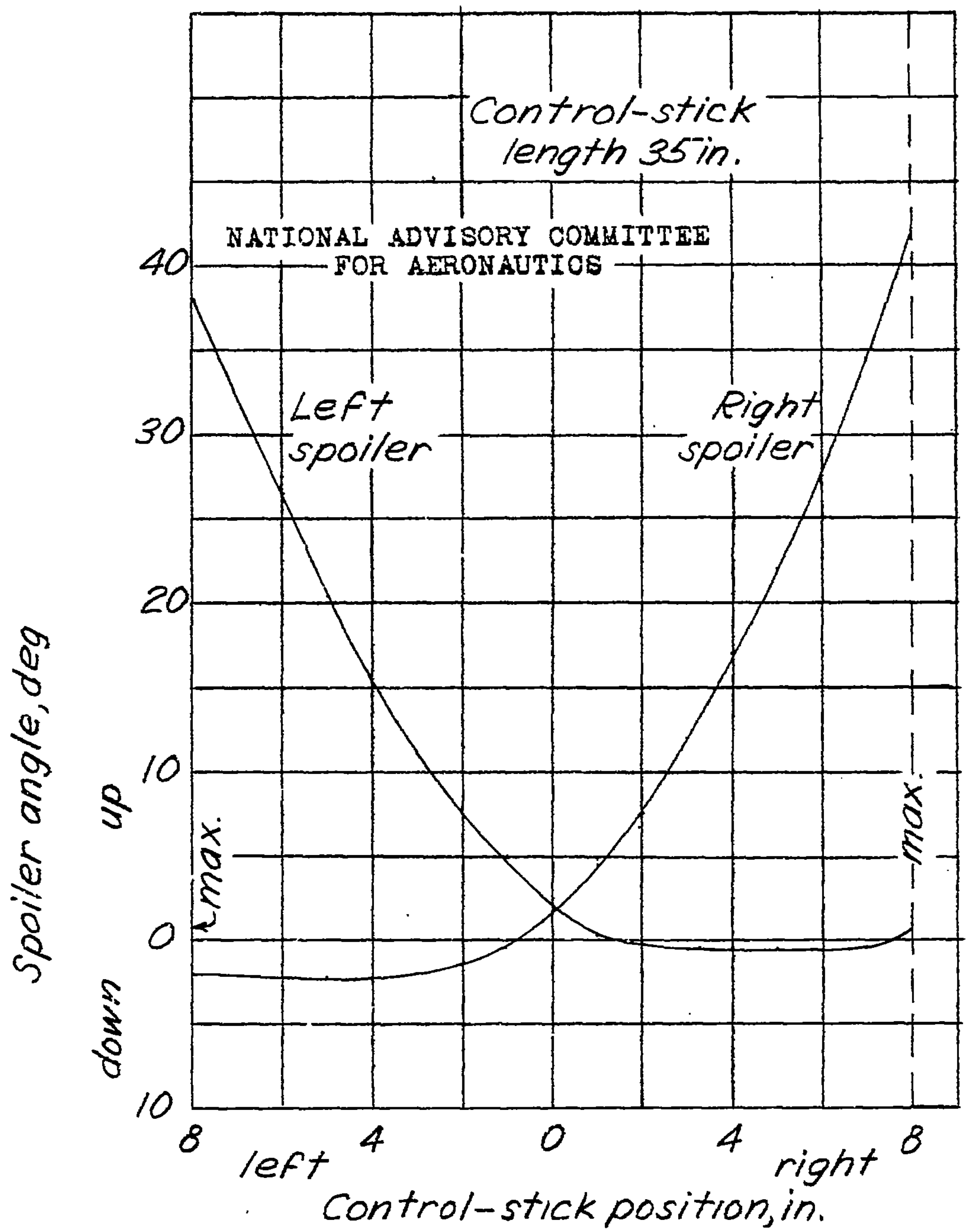


Figure 11.-Variation of spoiler angle with control-stick position under no-load condition. Arrangement III.

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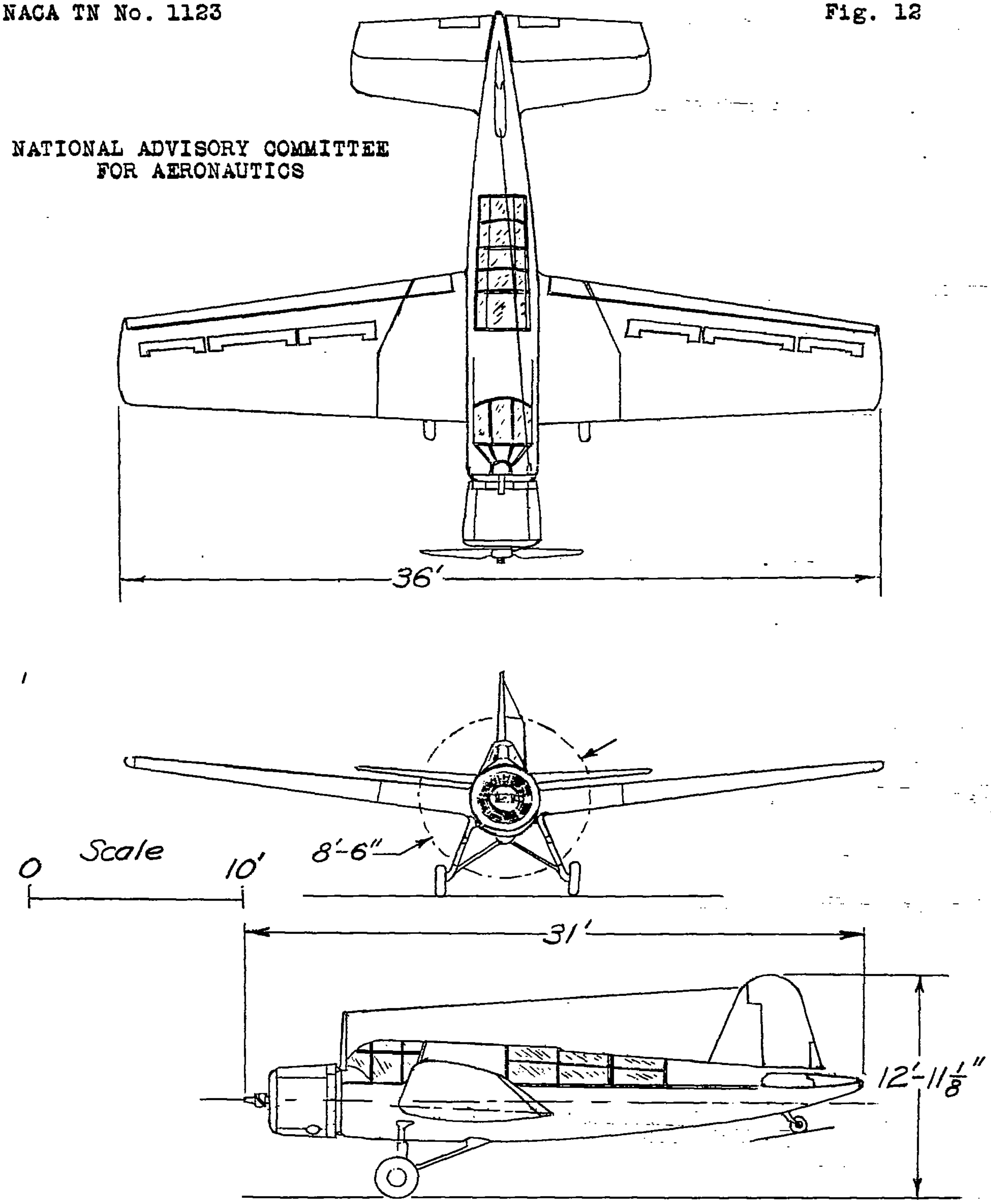
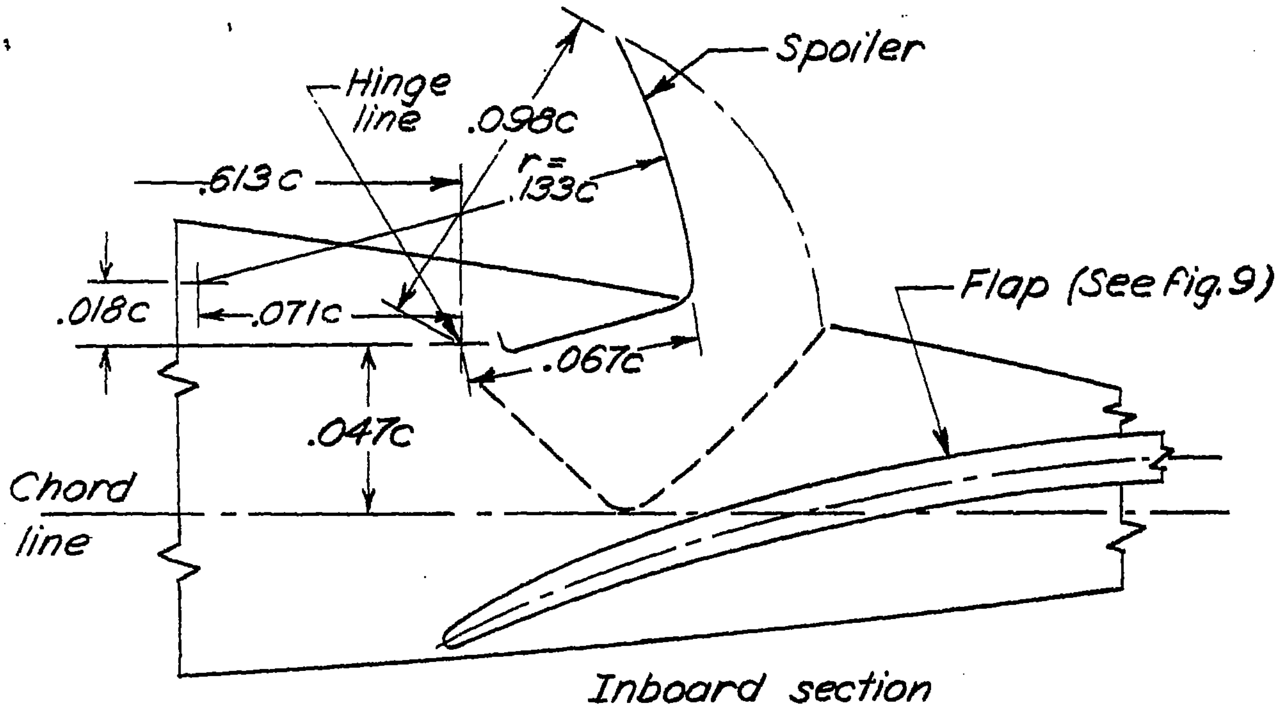


Figure 12.-Three-view drawing of the Vought-Sikorsky OS2U-2 (Zap) airplane. Arrangements III and IV.



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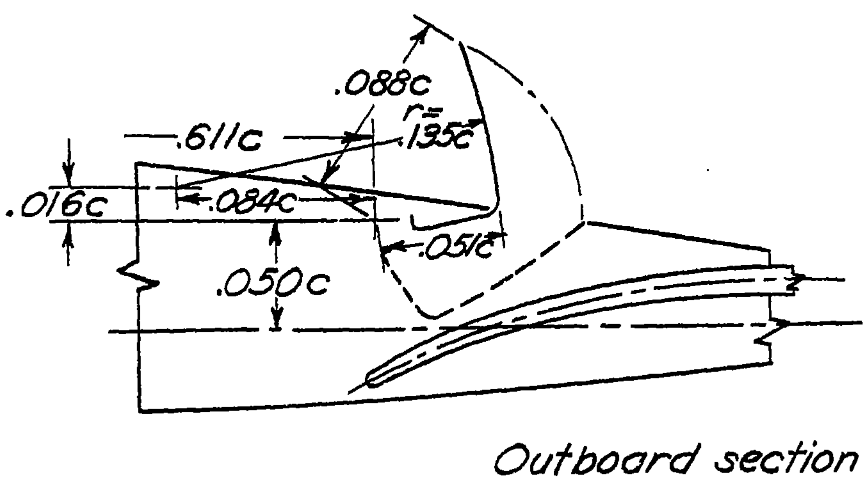


Figure 13.- Spoiler and flap, Arrangement IV

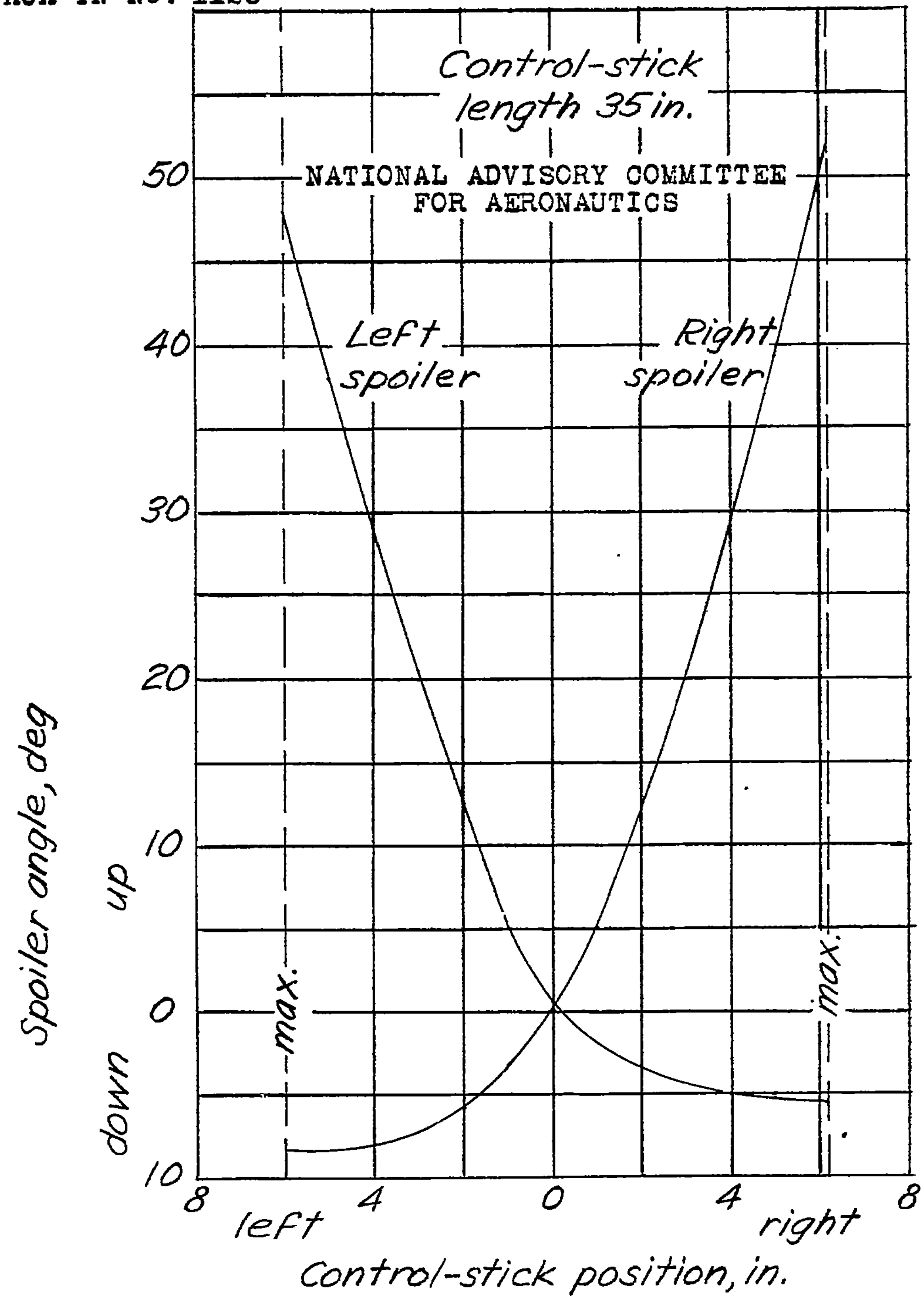
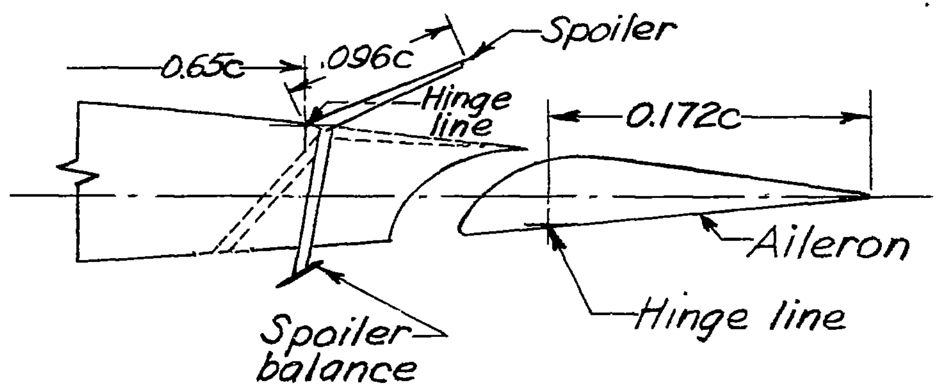


Figure 15.-Variation of spoiler angle with control-stick position under no-load condition. Arrangement IV.



Lateral control surfaces

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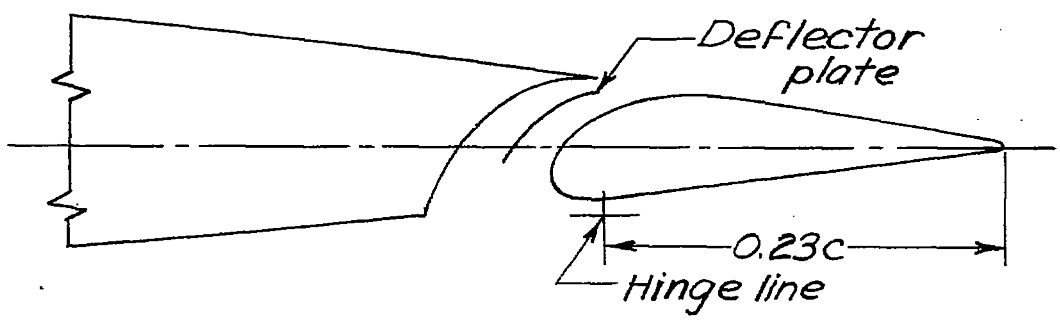


Flap

Figure 16.- Lateral control surfaces and flap.
Arrangement V.

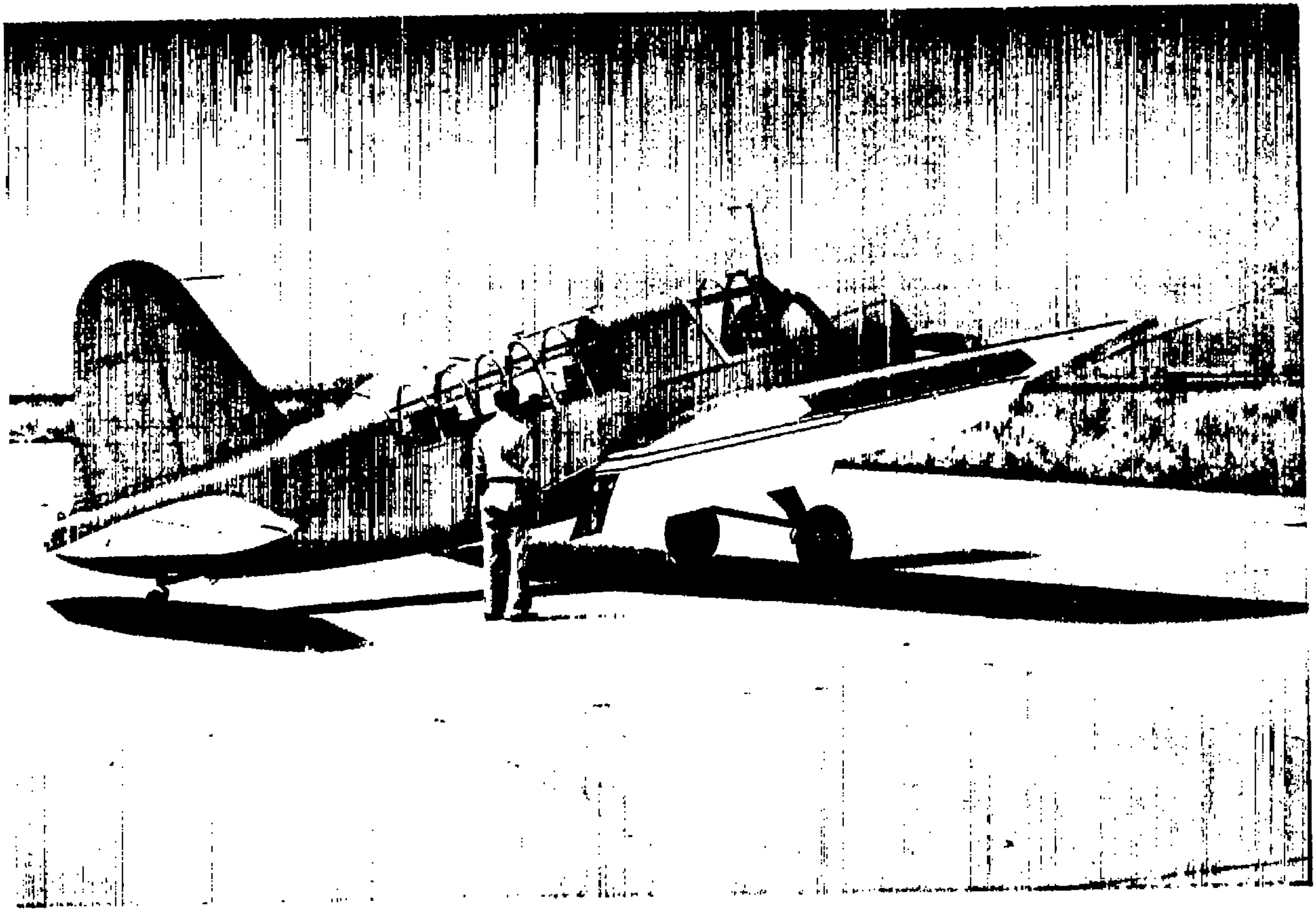


Figure 17.- Vought-Sikorsky OS2U-2 airplane with spoilers and flaps fully deflected. Arrangement V.

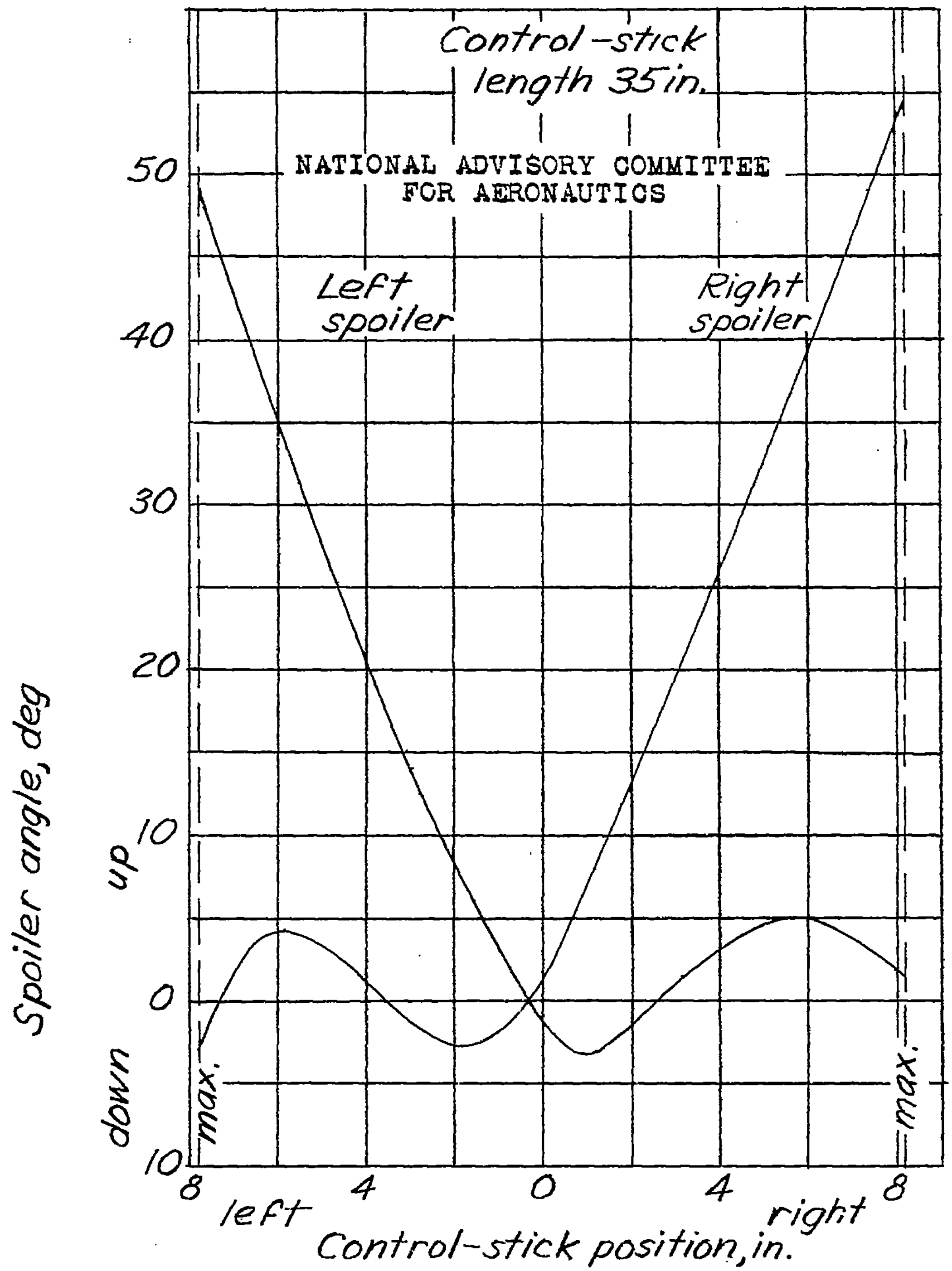


Figure 18.-Variation of spoiler angle with control-stick position under no-load condition. Arrangement V.

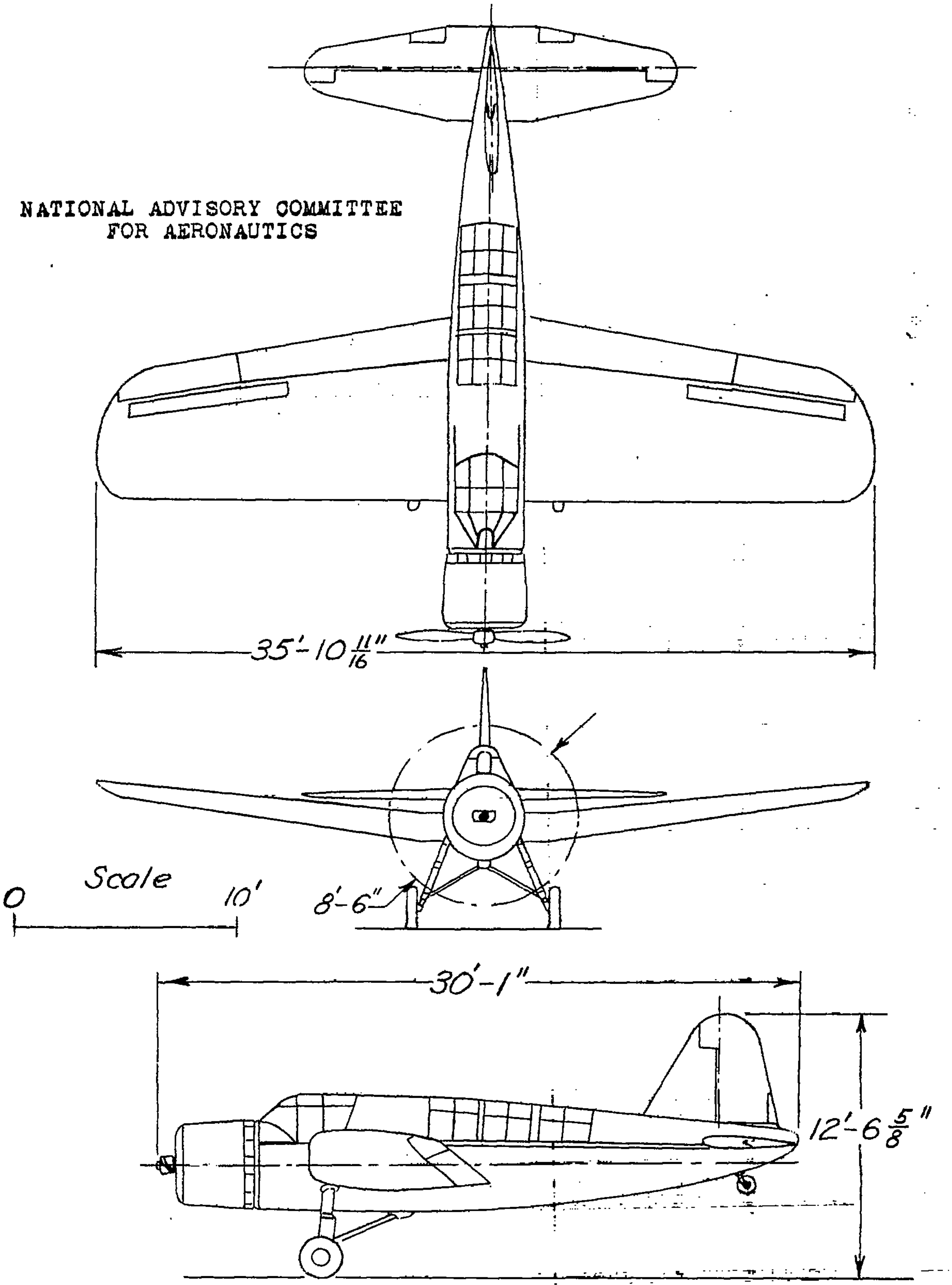
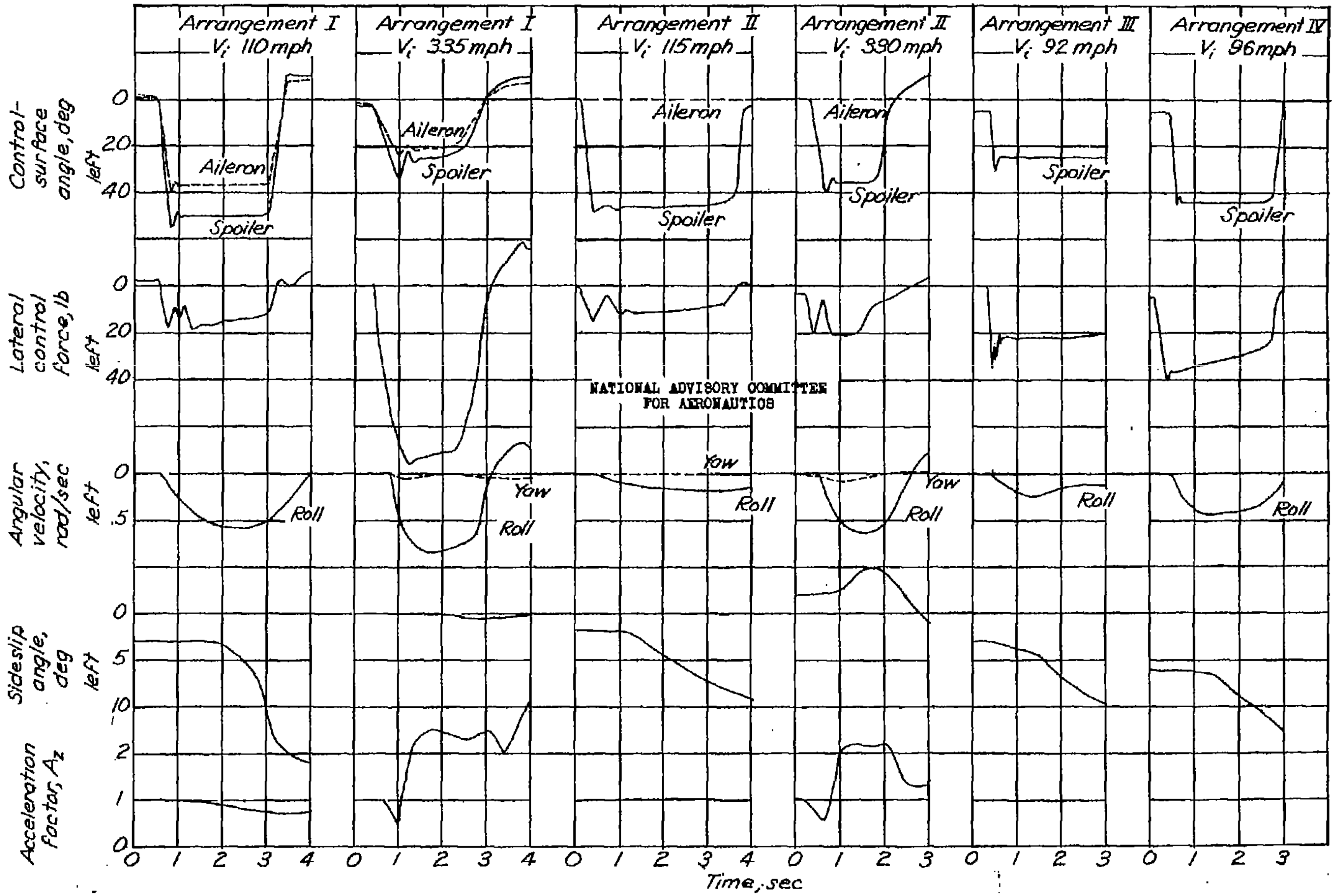
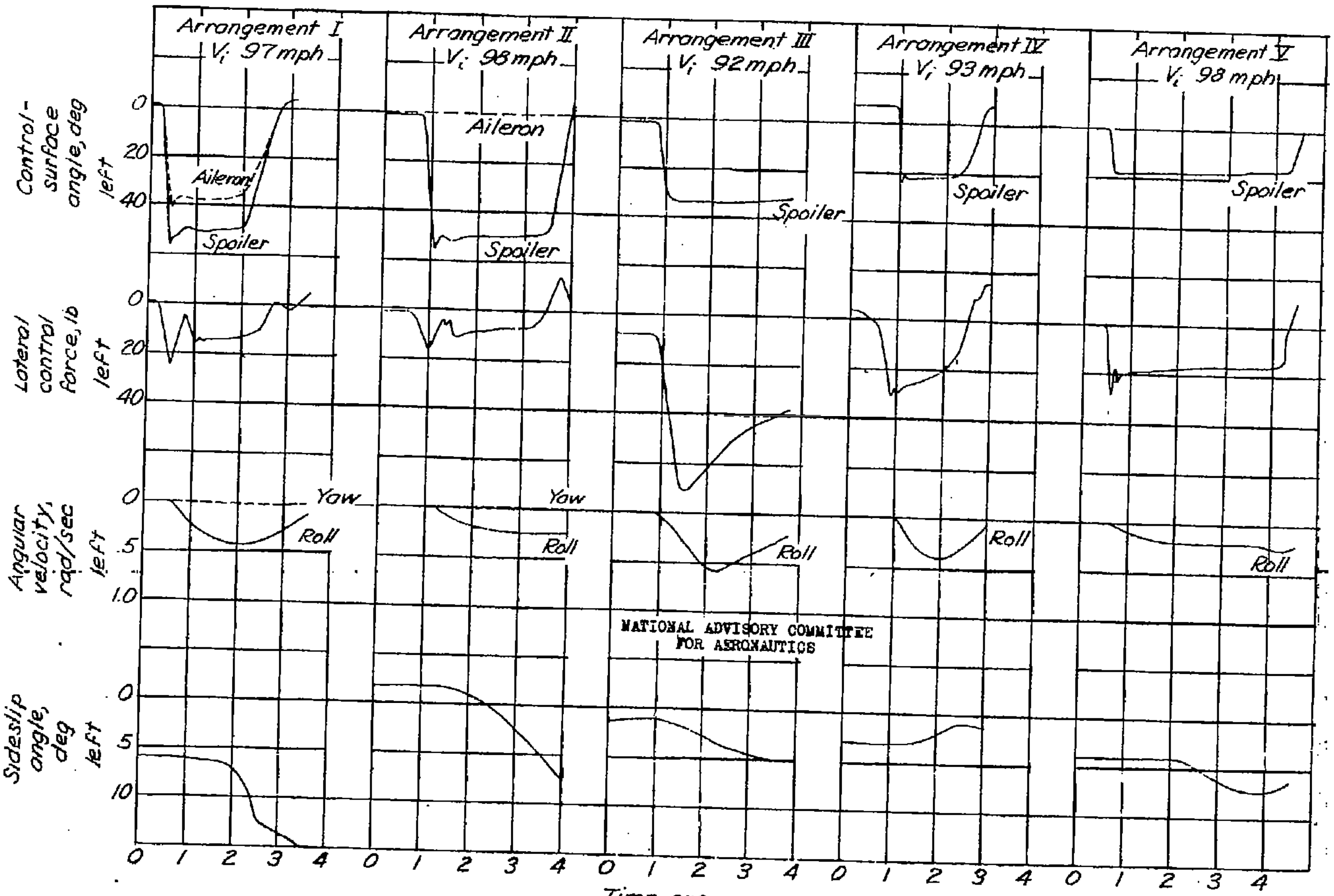


Figure 19.- Three-view drawing of the Vought-Sikorsky OS2U-2 airplane. Arrangement V.



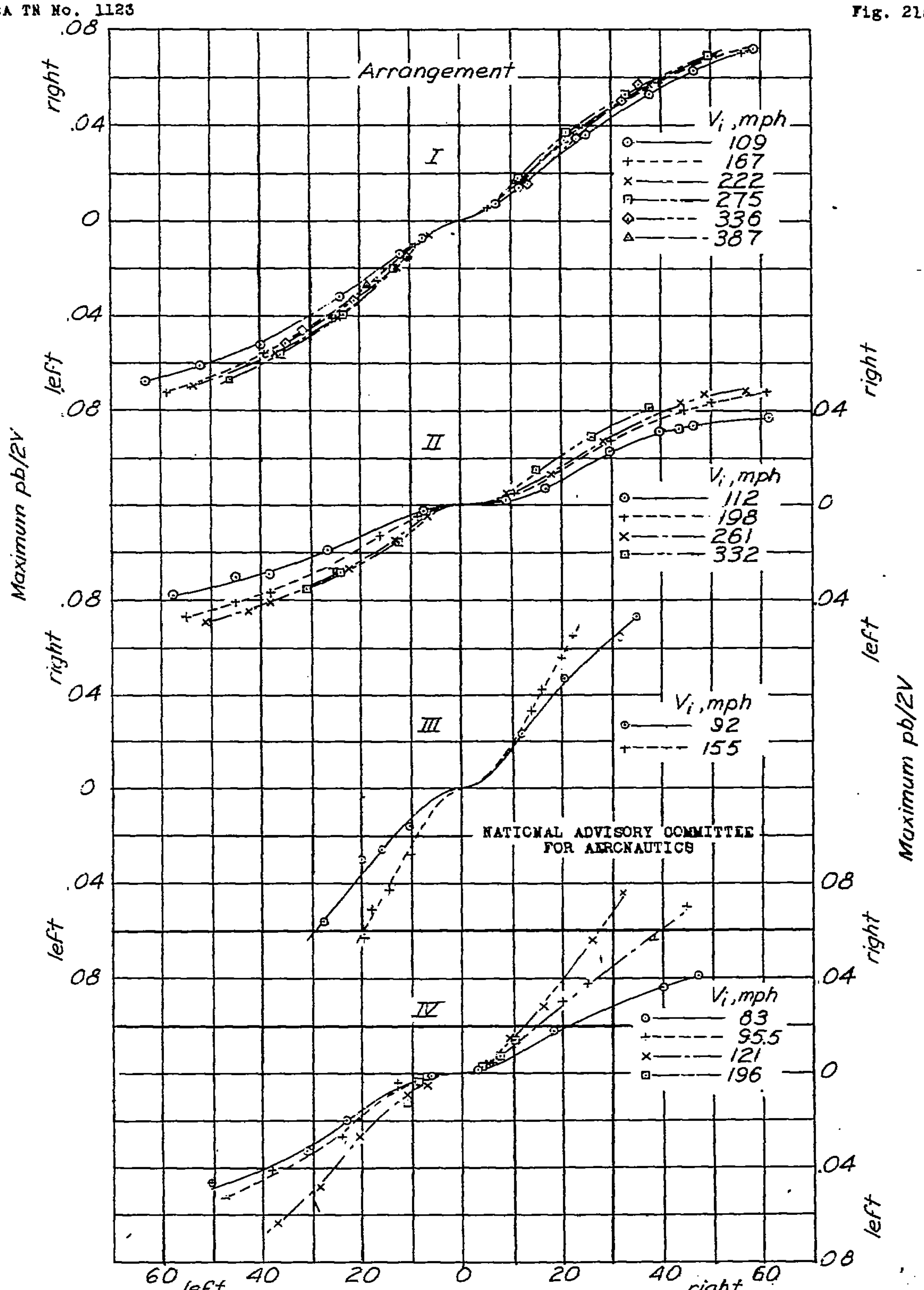
(a) Power-on clean condition.

Figure 20.- Time histories of abrupt rudder-fixed rolls.



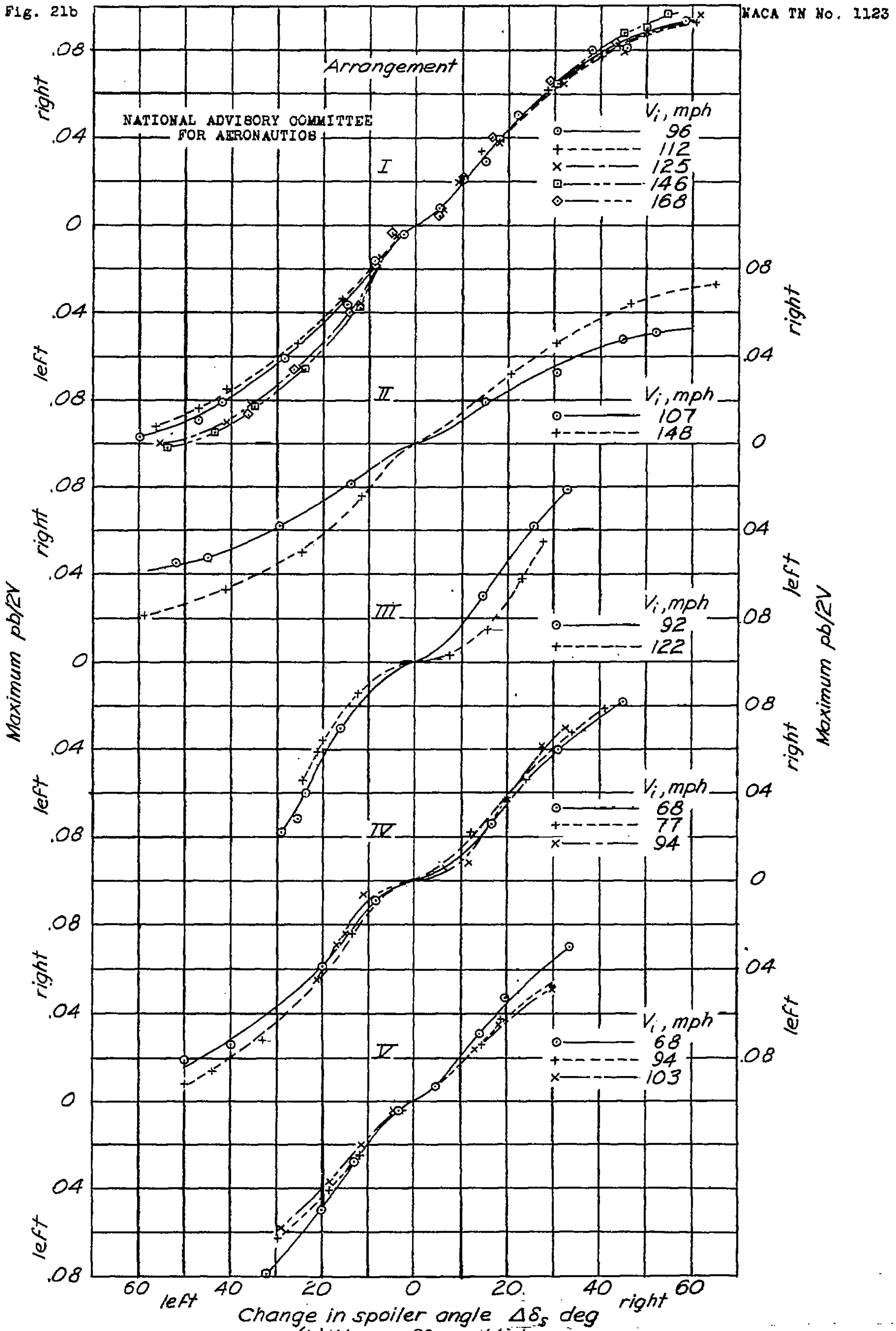
(b) Wave-off condition.

Figure 20.–Concluded.

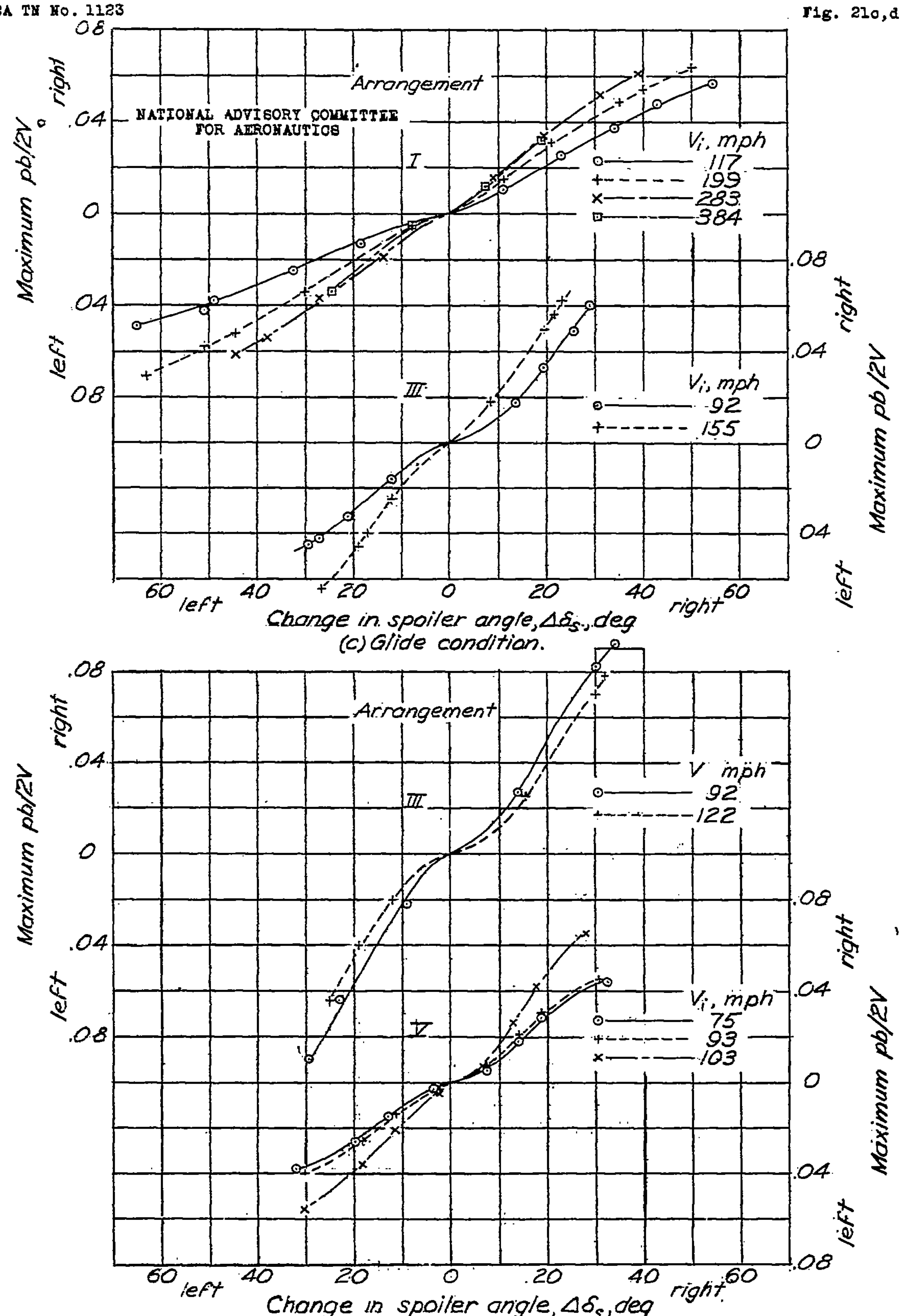


(a) Power-on clean condition.

Figure 21 – Variation of maximum pb/2V with spoiler angle in abrupt rudder-fixed rolls.



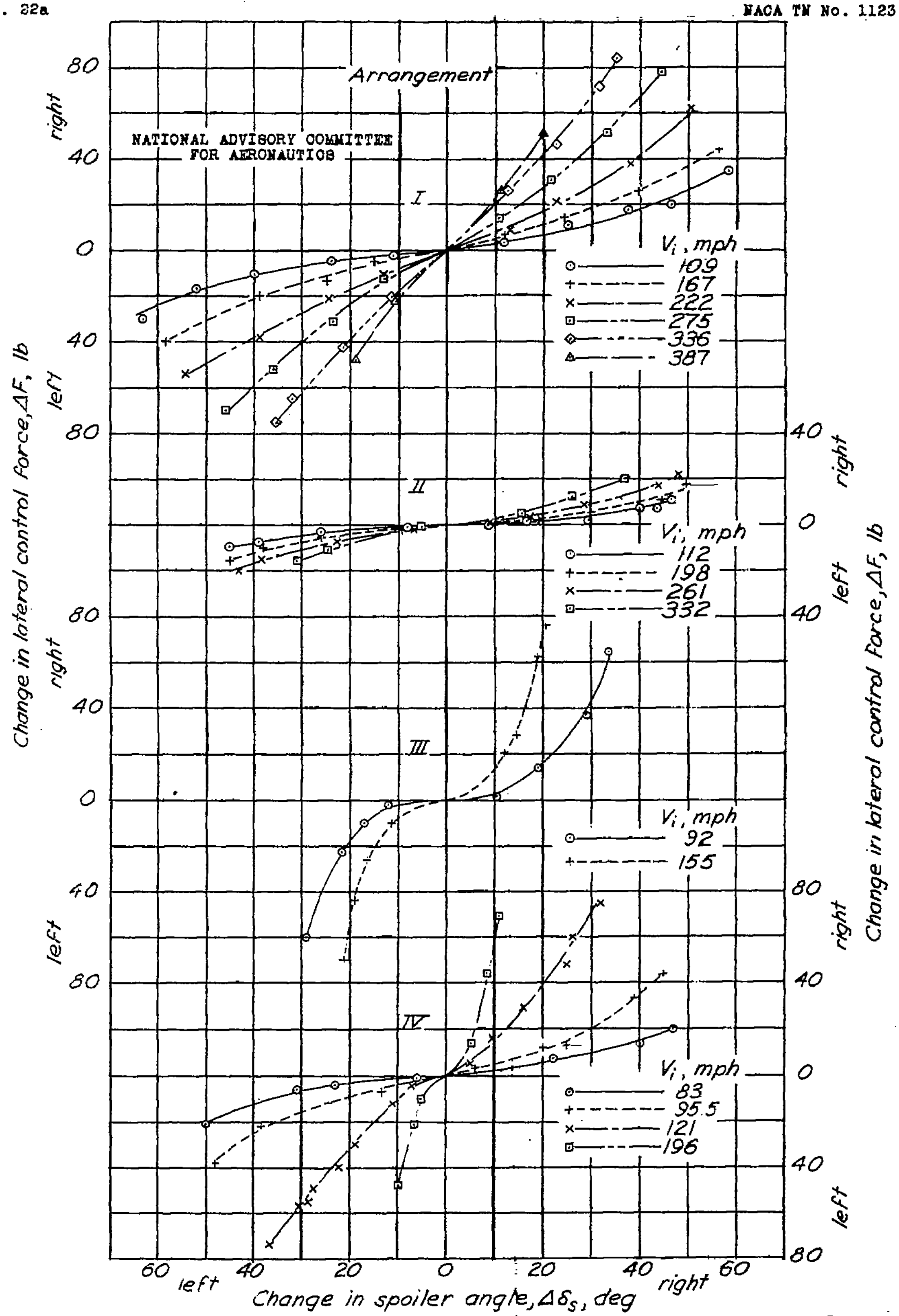
(b) Wave-off condition.
Figure 21 .- Continued



(c) Glide condition.

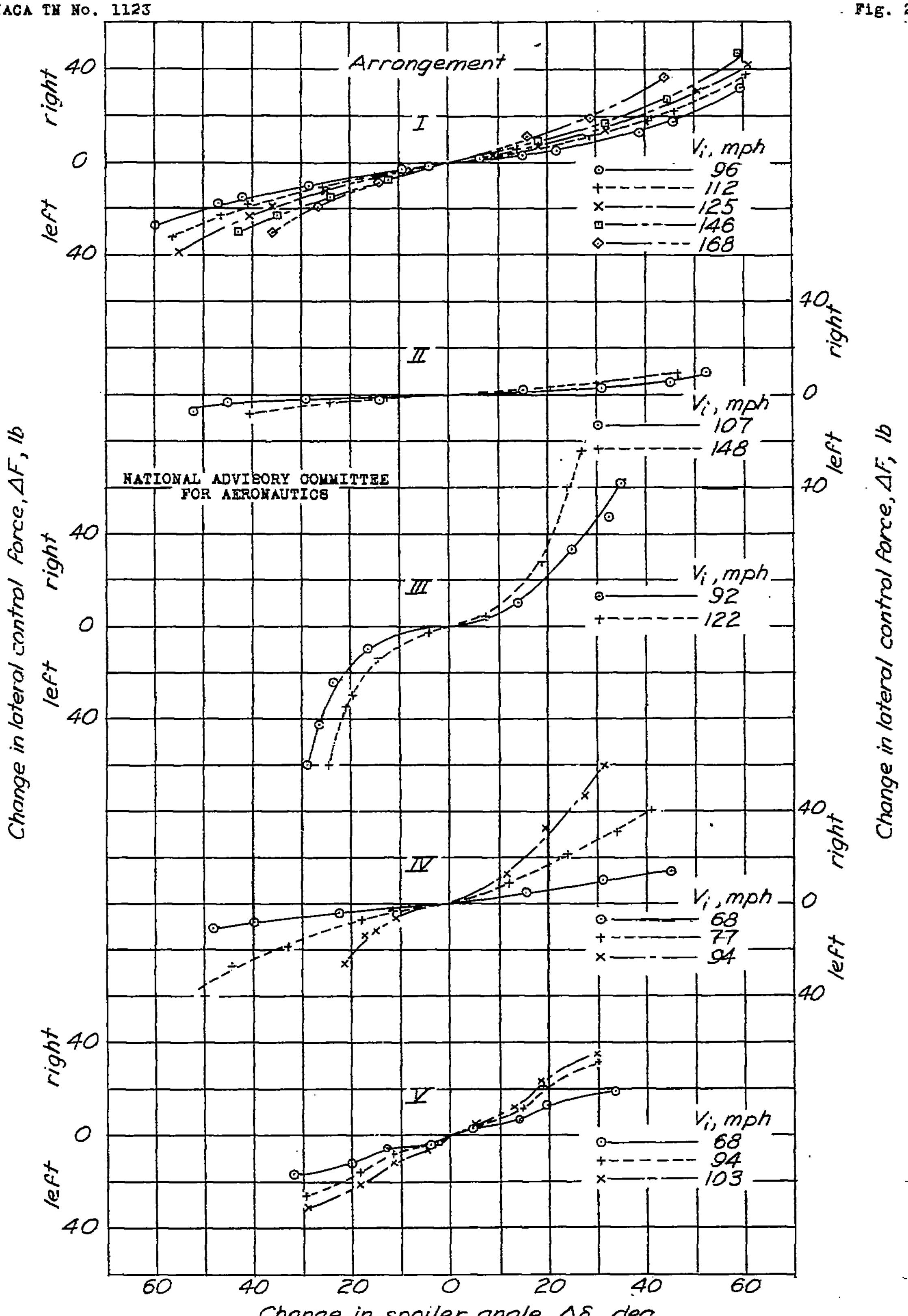
(d) Landing condition.

Figure 21 - Concluded.



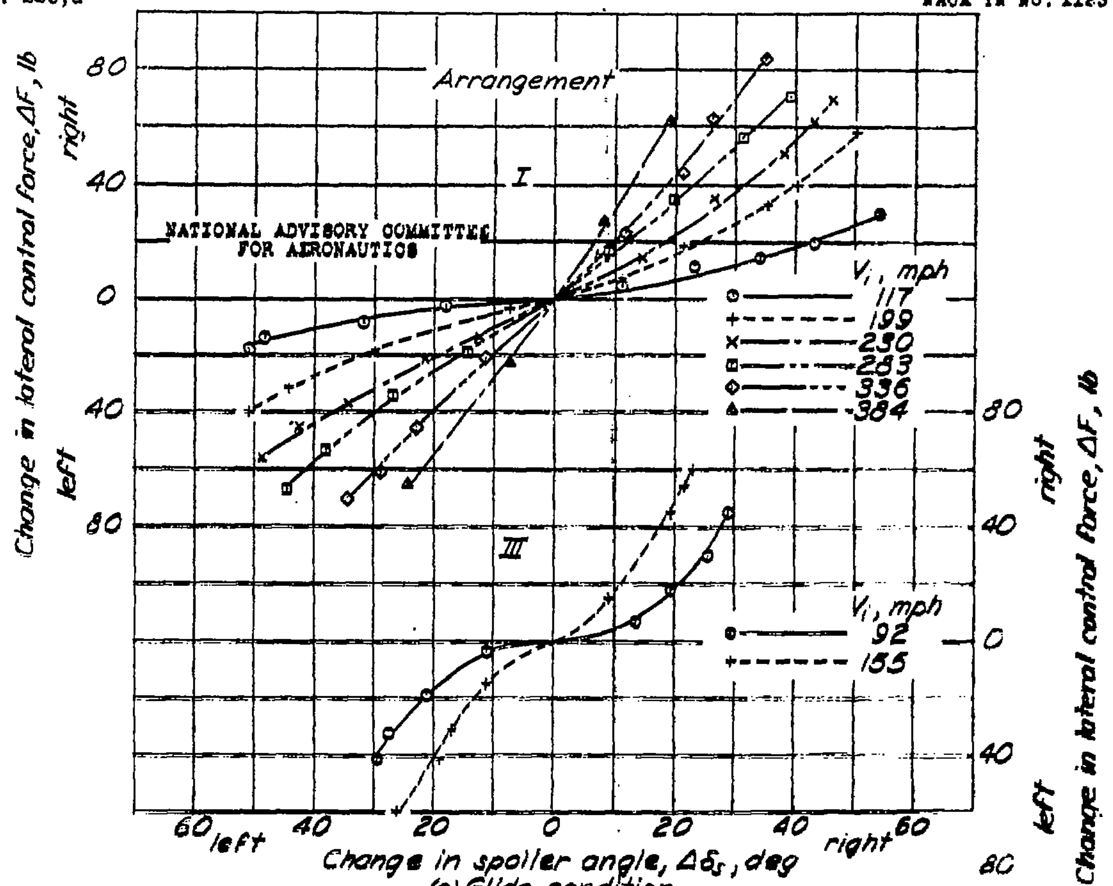
(a) Power-on clean condition.

Figure 22.-Variation of lateral control force with spoiler angle in abrupt rudder-fixed rolls.

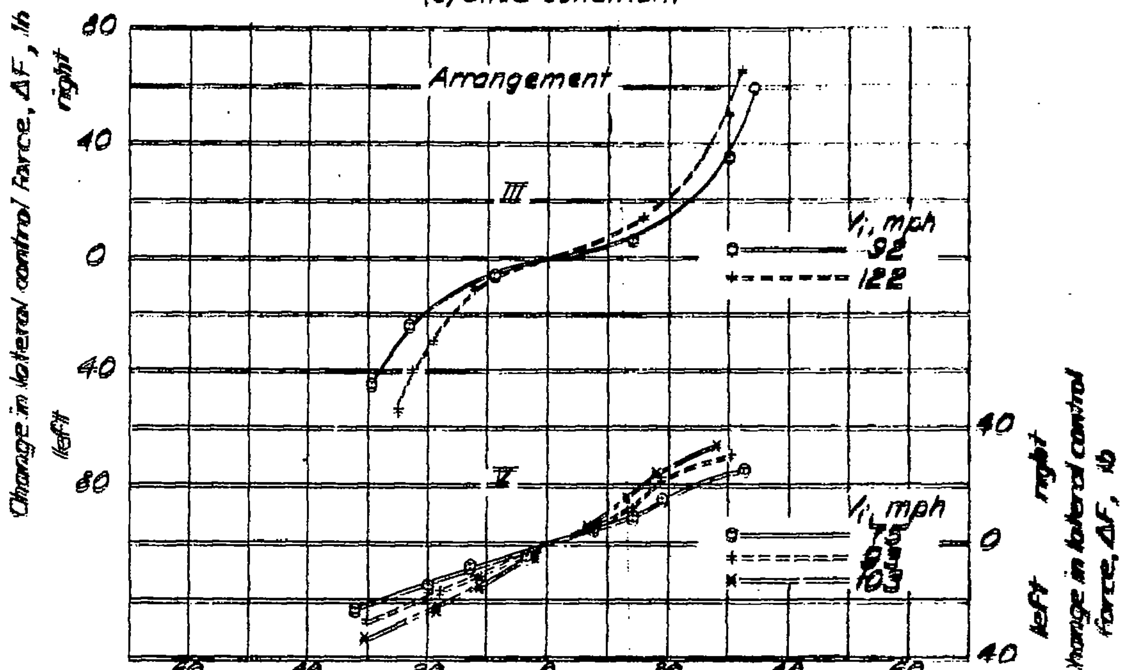


(b) Wave-off condition

Figure 22 - Continued.

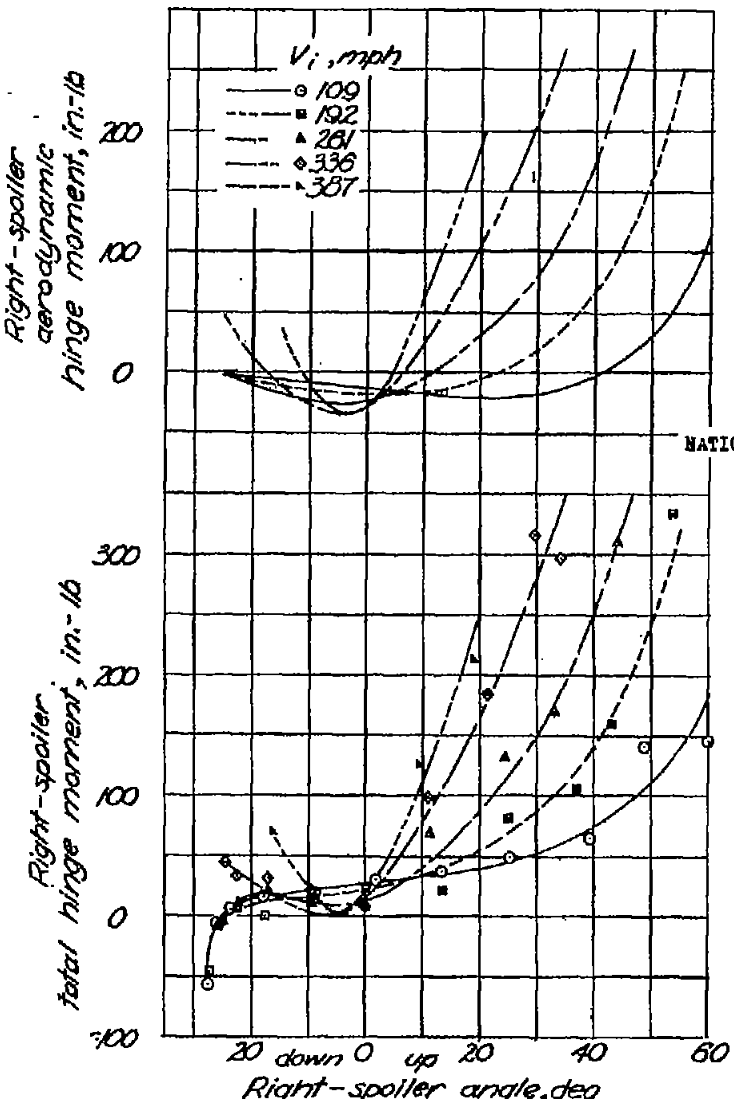


(c) Glide condition.



(d) Landing condition.

Figure 22.- Concluded.



(a) Power-on clean condition.

Figure 23.- Variation of right-spoiler aerodynamic and total hinge moment with spoiler angle in abrupt rudder-fixed rolls. Arrangement I

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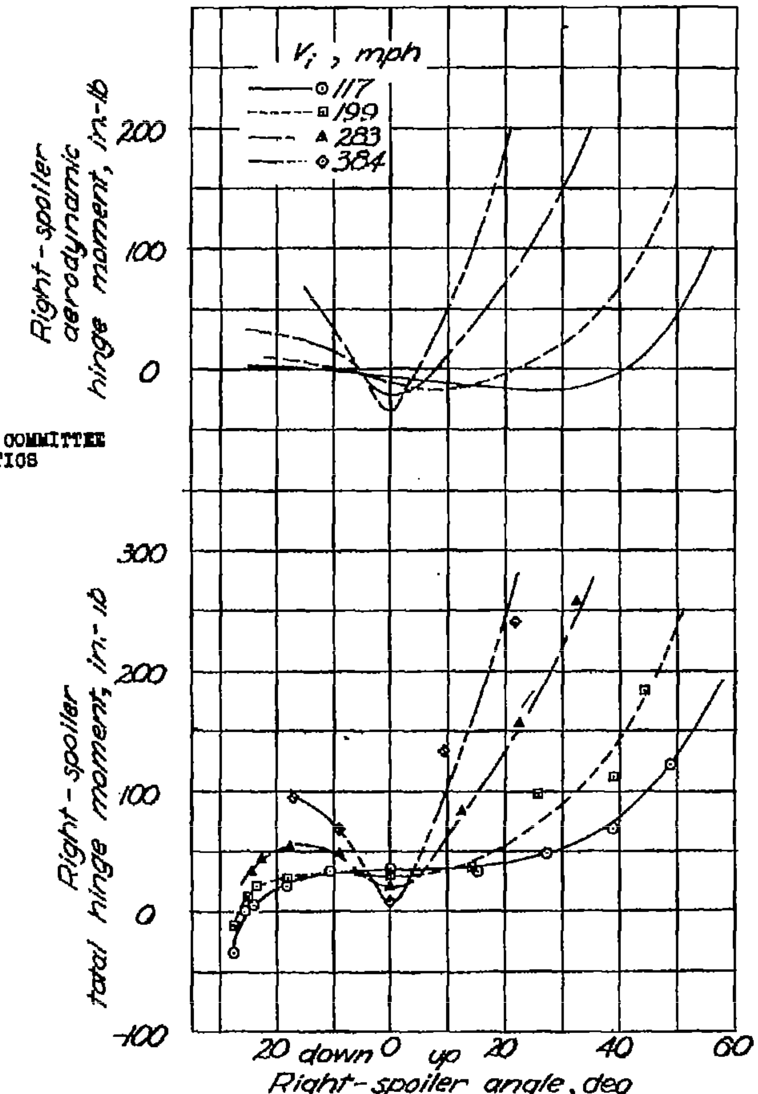
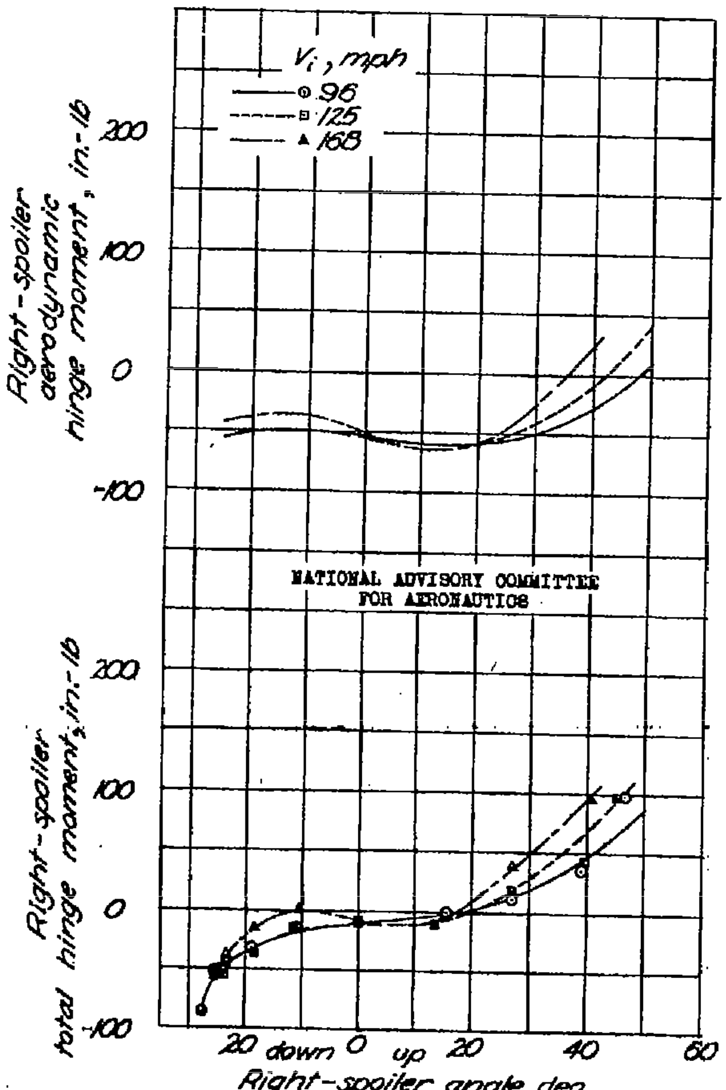


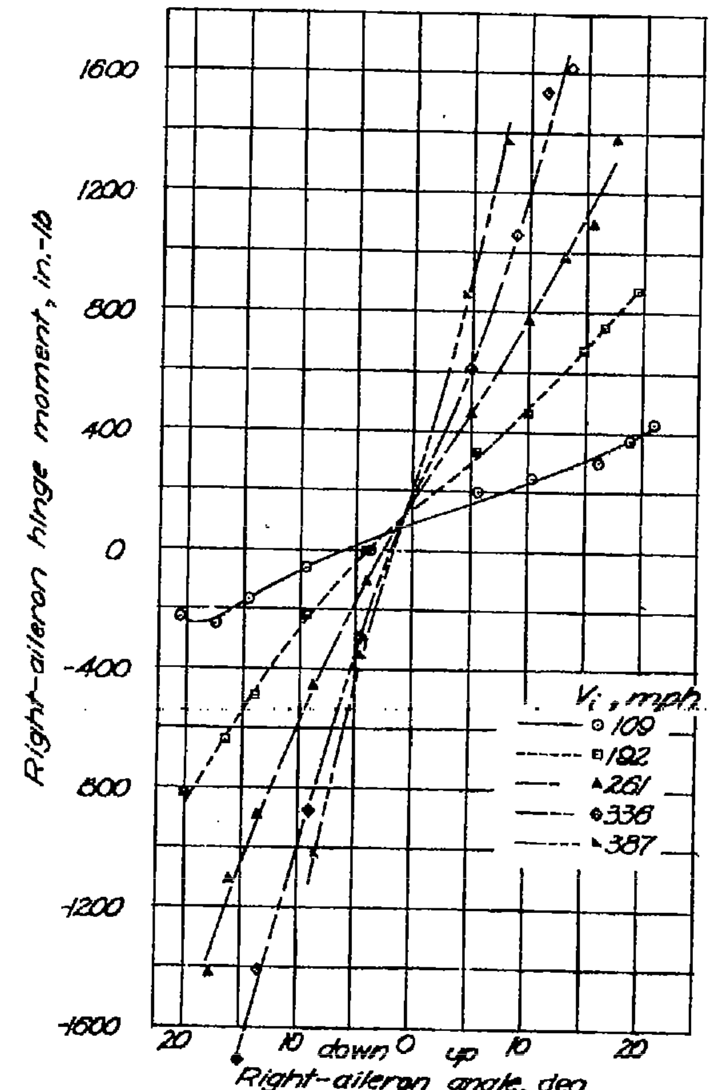
(b) Glide condition.

Figure 23.- Continued.



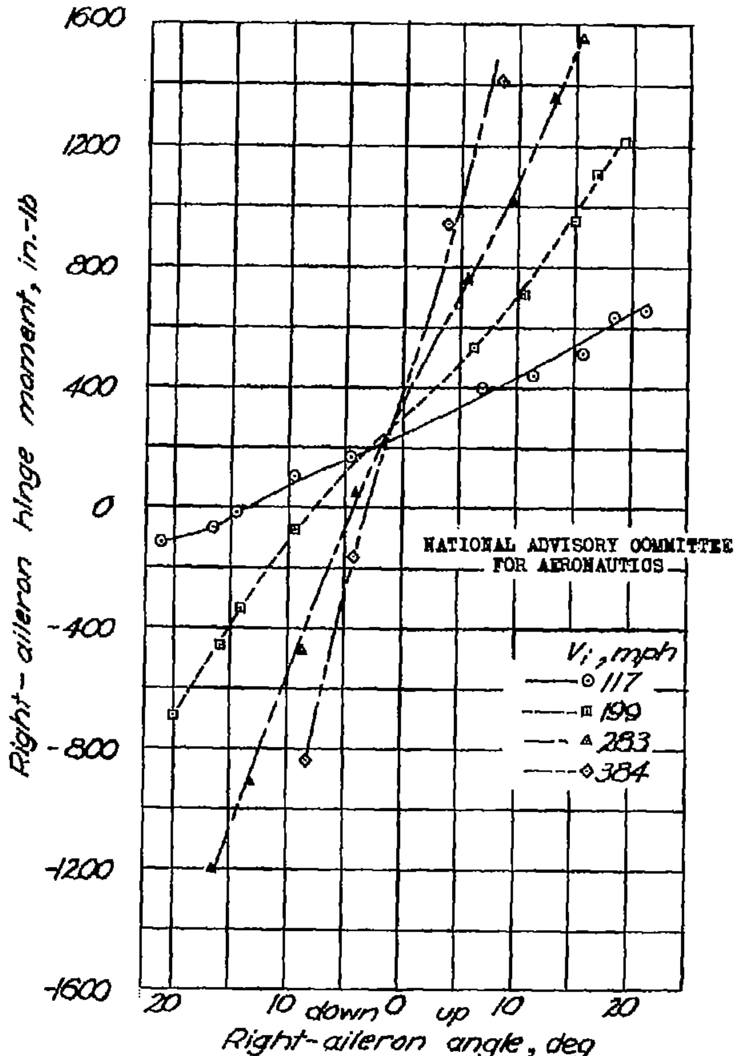
(c) Wave-off condition.

Figure 23.- Concluded.



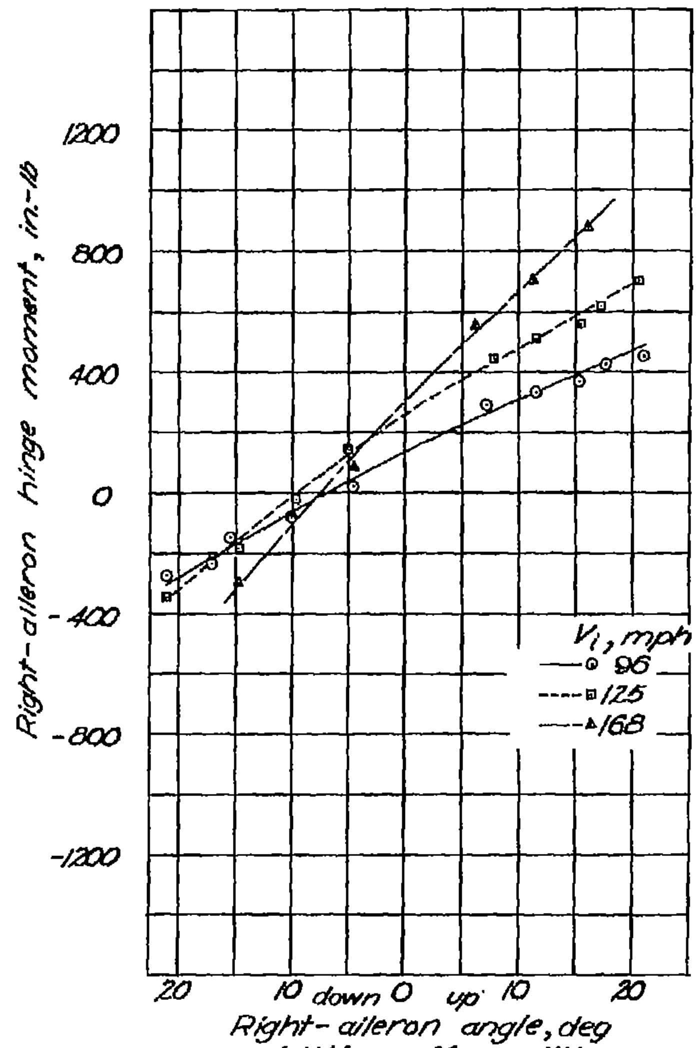
(a) Power-on clean condition.

Figure 24.-Variation of right-aileron hinge moment with aileron angle in abrupt rudder-fixed rolls Arrangement I.



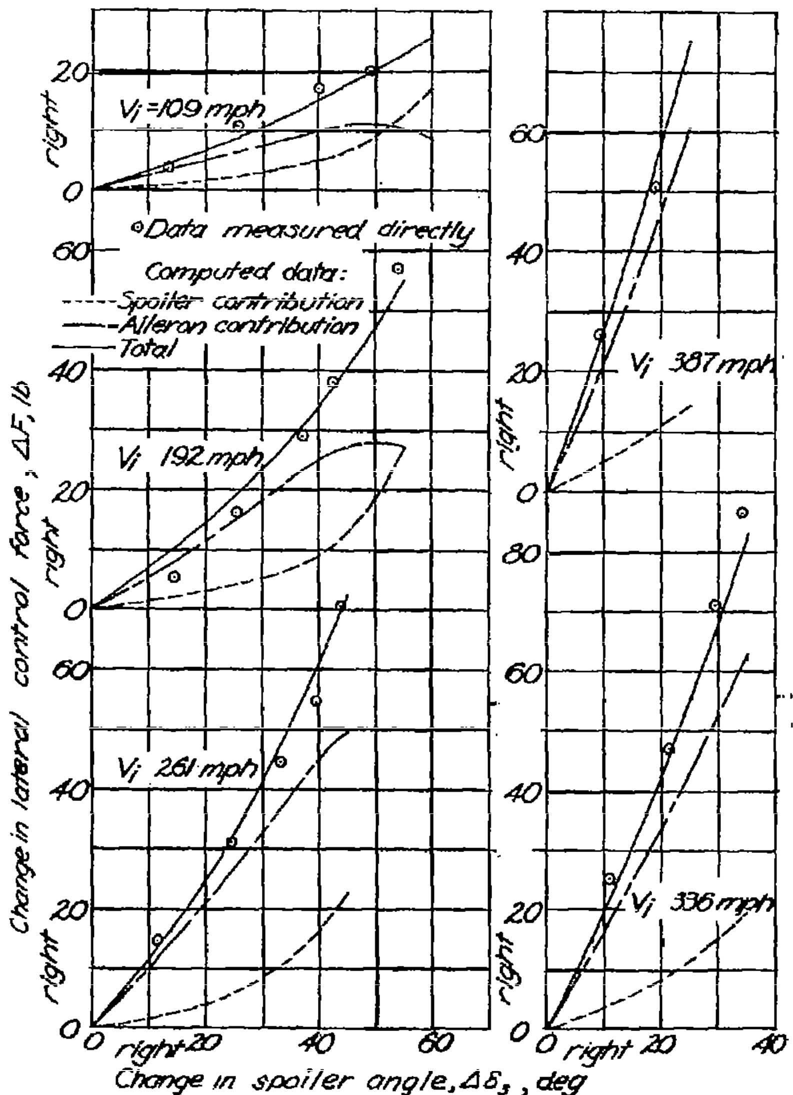
(b) Glide condition.

Figure 24.- Continued.



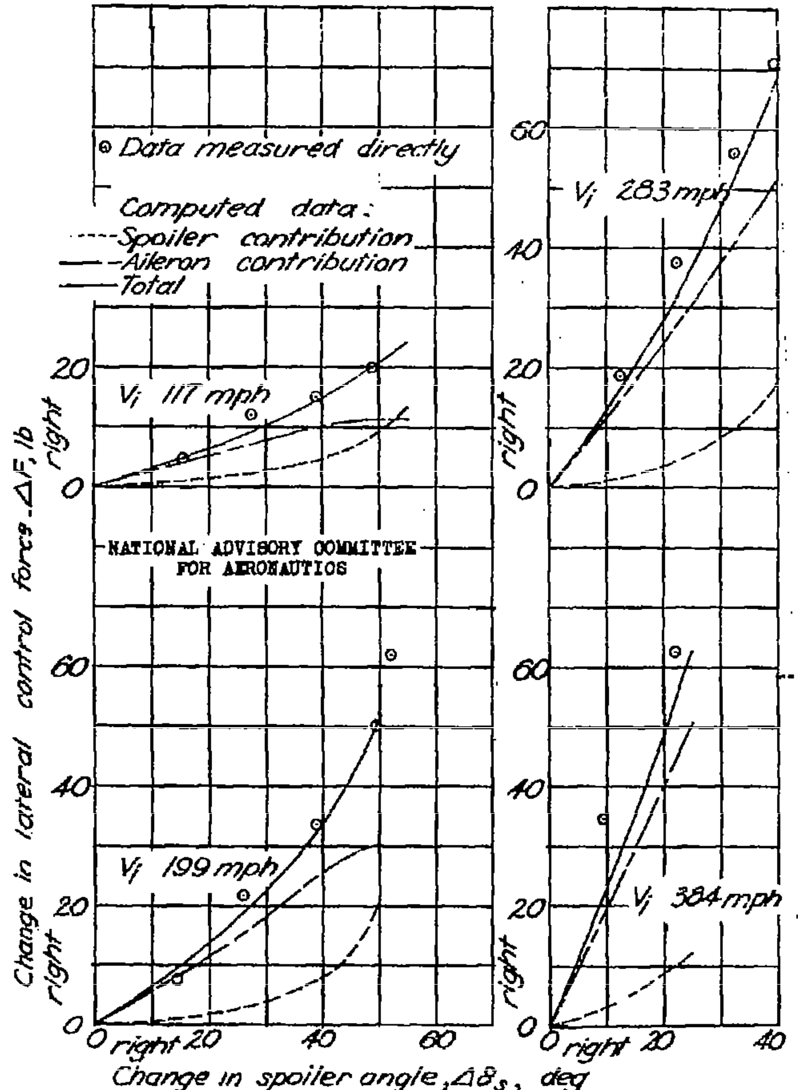
(c) Wave-off condition.

Figure 24.- Concluded.



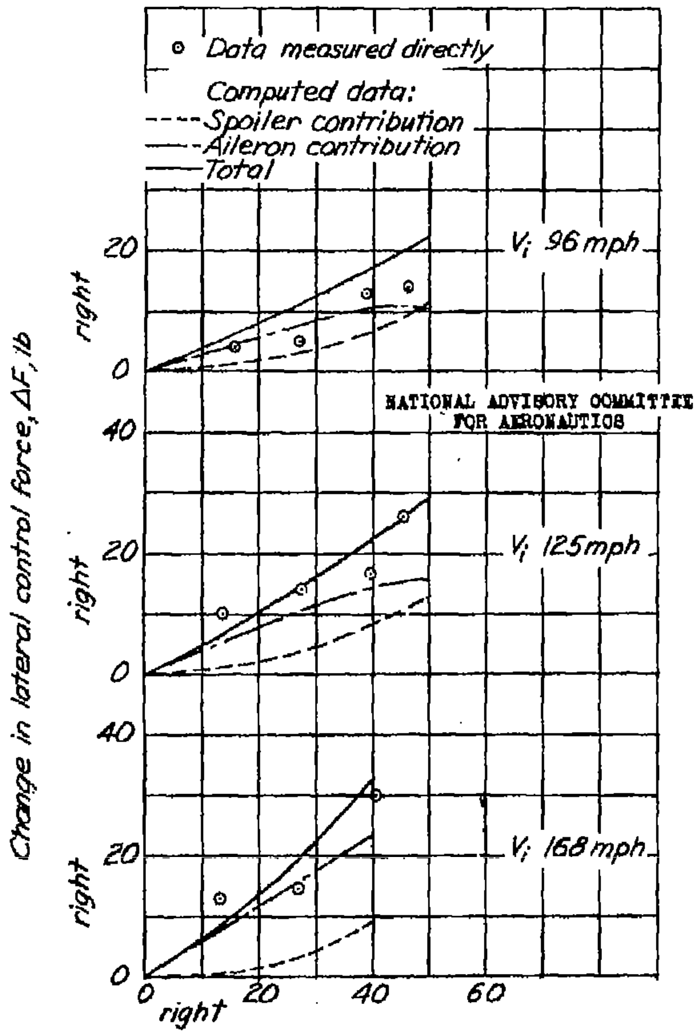
(a) Power-on clean condition.

Figure 25.- Variation with spoiler angle of lateral control force, as computed from hinge-moment data in abrupt rudder-fixed rolls. Arrangement I.



(b) Glide condition.

Figure 25.- Continued.



(c) Wave-off condition.

Figure 25.- Concluded.

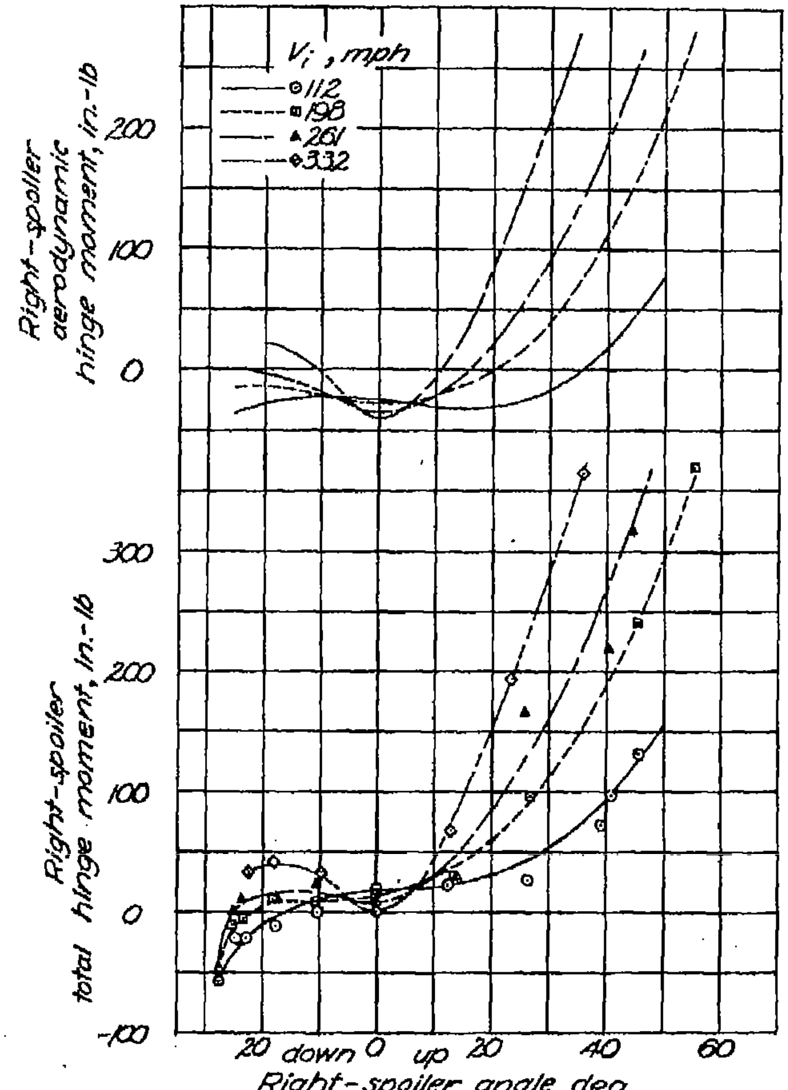
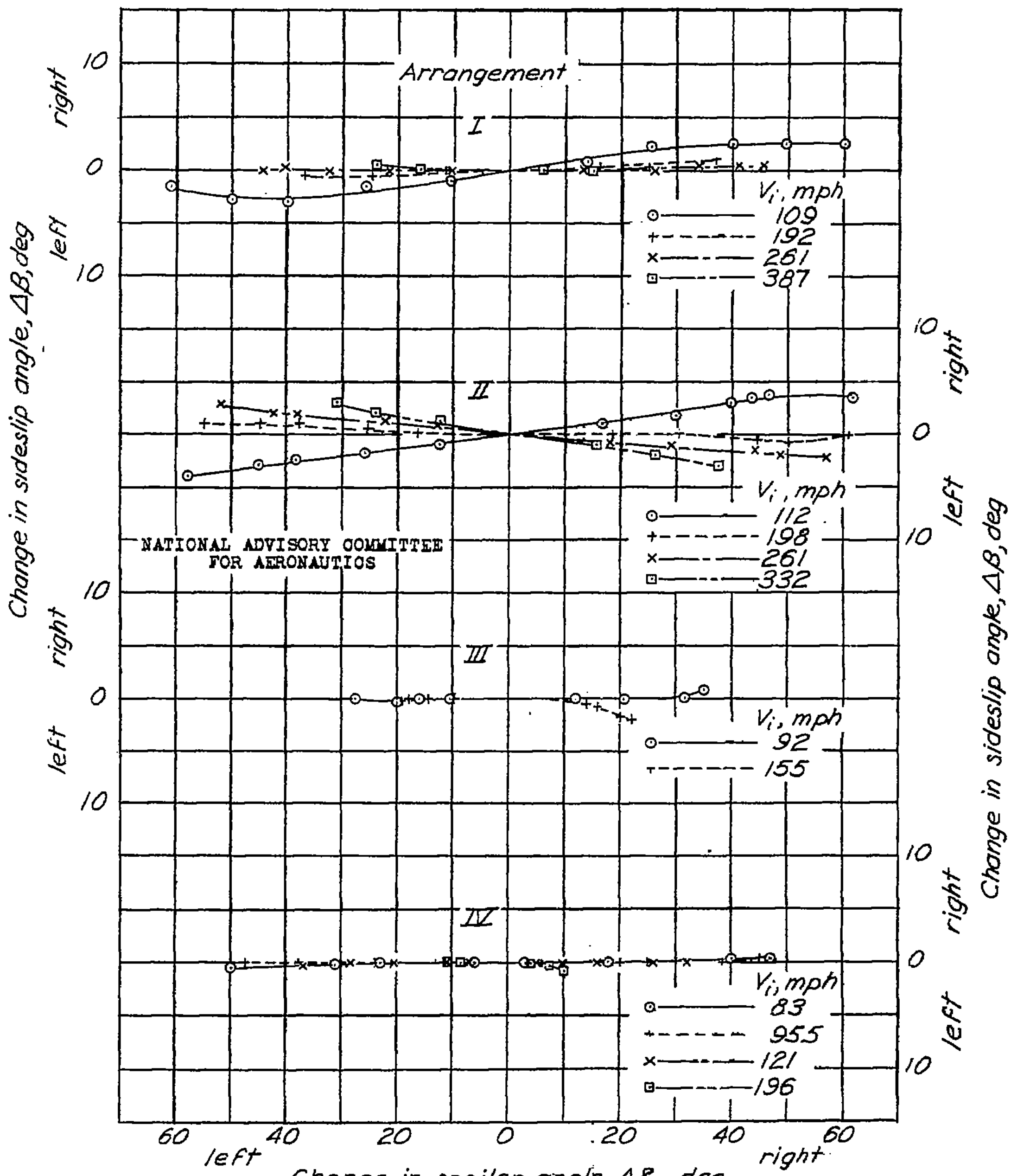
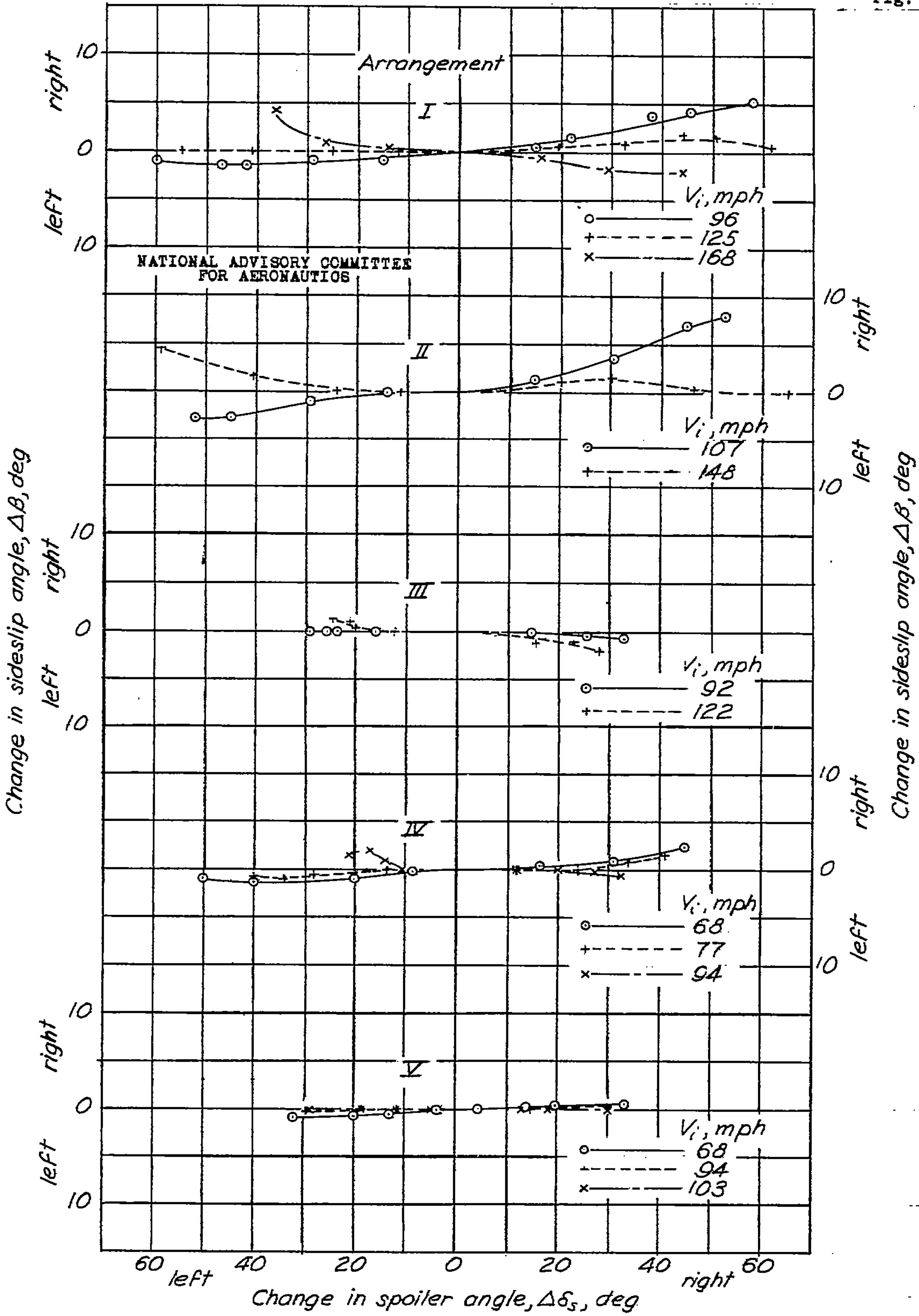


Figure 26.- Variation of right-spoiler aerodynamic and total hinge moment with spoiler angle in abrupt rudder-fixed rolls, power-on clean condition. Arrangement II.



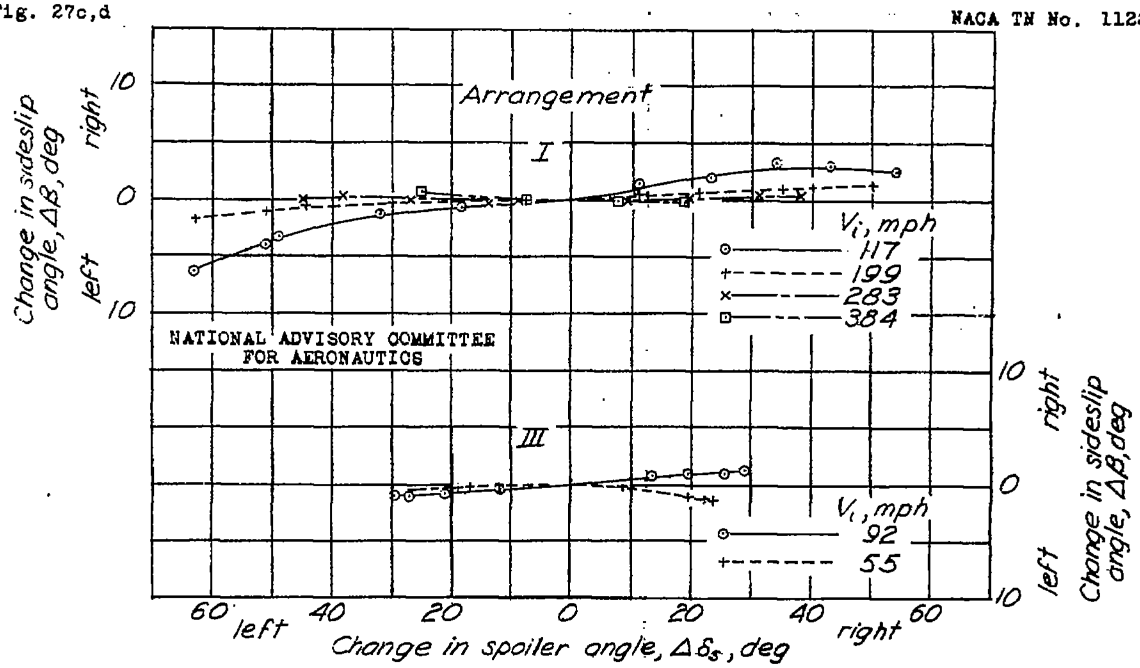
(a) Power-on clean condition.

Figure 27.-Variation of sideslip angle with spoiler angle in abrupt rudder-fixed rolls.

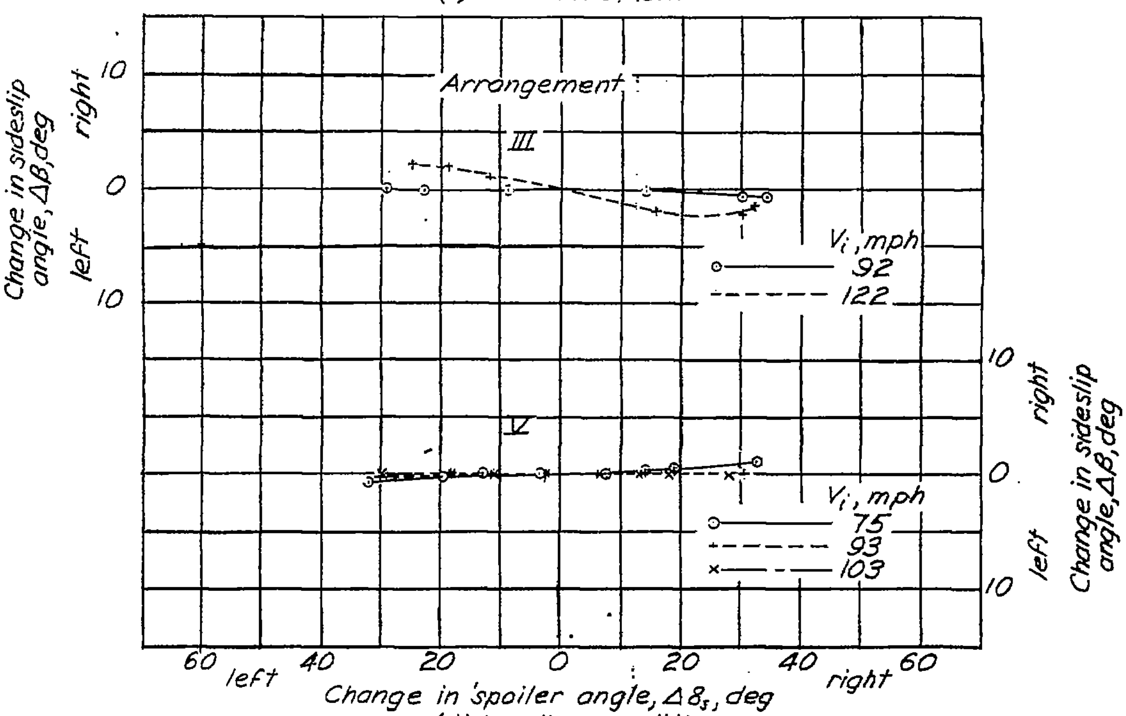


(b) Wave-off condition.

Figure 27.- Continued.



(c) Glide condition.



(d) Landing condition.

Figure 27.- Concluded.

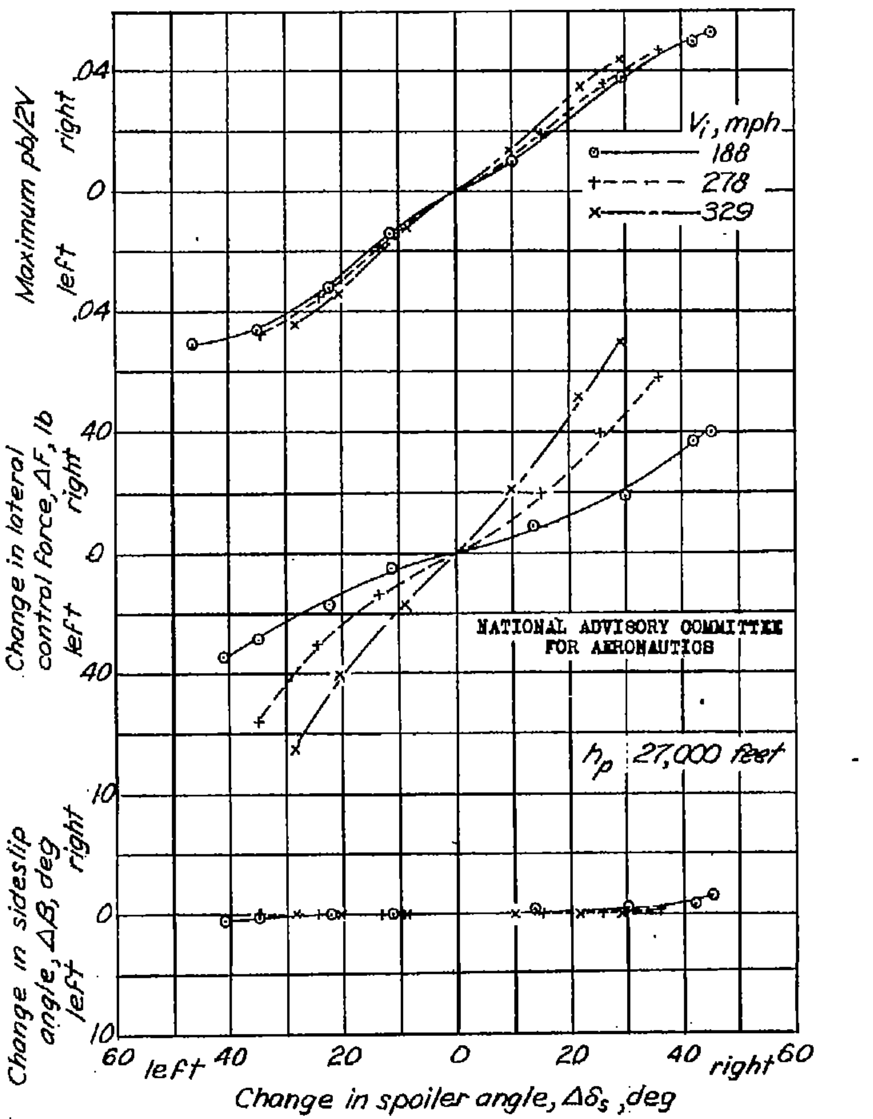


Figure 28.- Variation of maximum pb/2V, control force, and sideslip angle with spoiler angle in abrupt rudder-fixed rolls at high altitude, power-on clean condition. Arrangement I

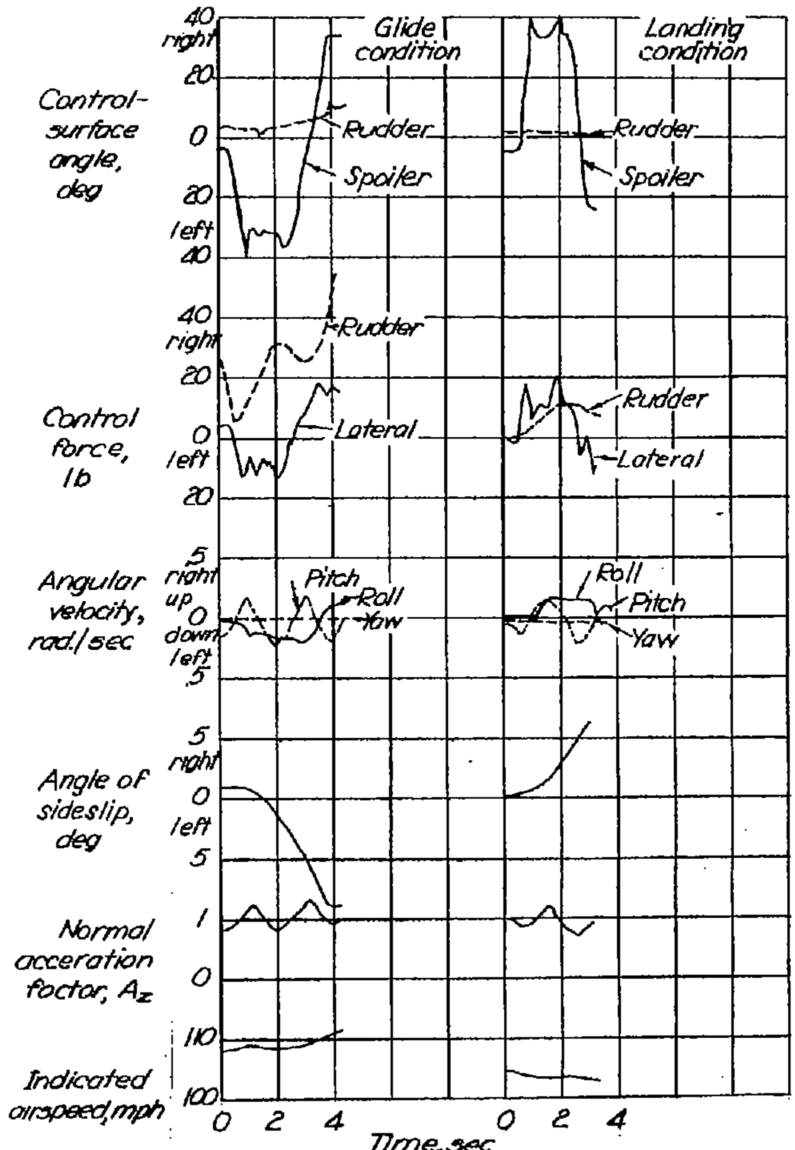


Figure 29.- Time histories of abrupt rudder-fixed rolls near stall. Arrangement I.

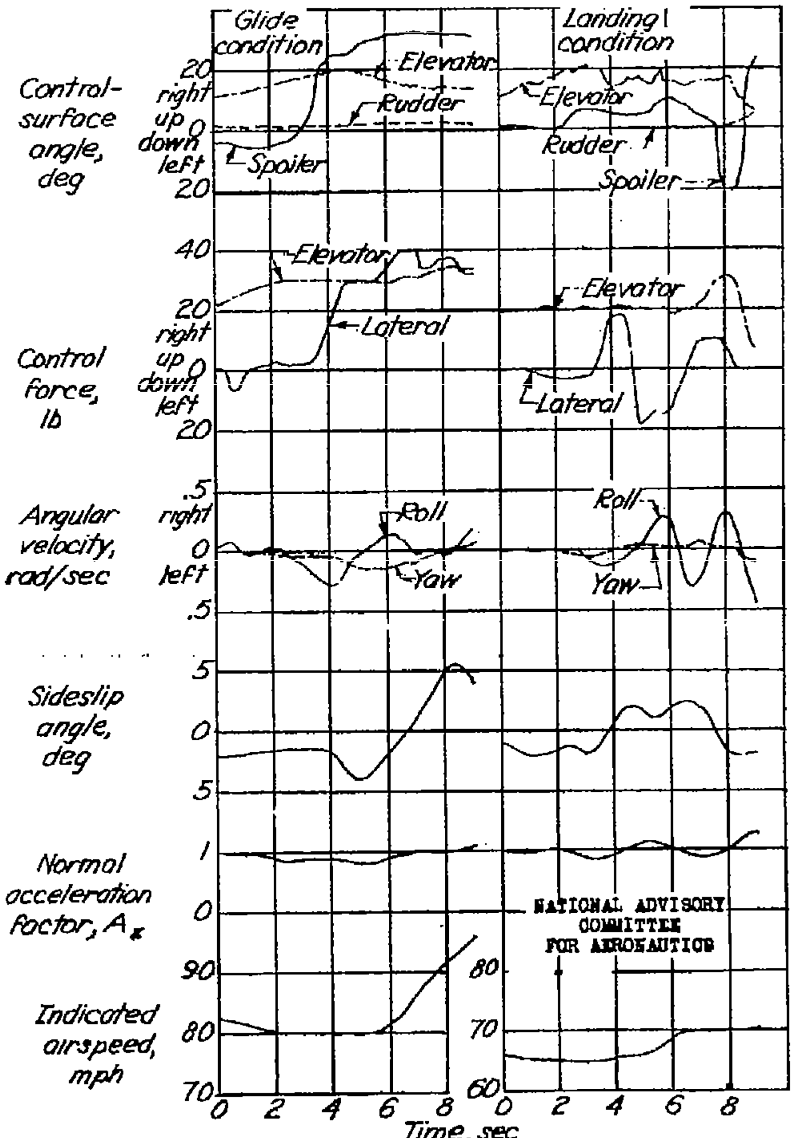


Figure 30.- Time histories of stalls in which spoilers alone were used to attempt control. Arrangement III.

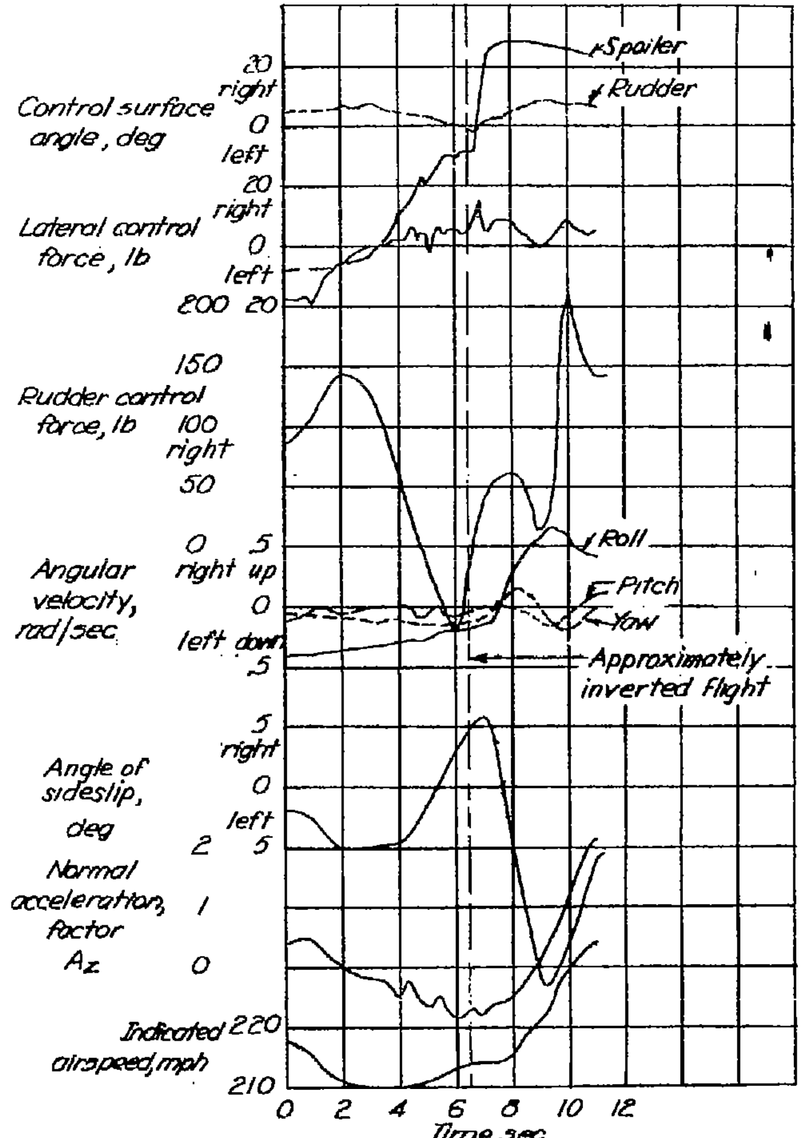


Figure 31.-Time history of a maneuver showing the spoiler effectiveness in approximately inverted flight, power-on clean condition. Arrangement II.